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Technical review of the REnescience process

for CURE Afvalbeheer in The Netherlands

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Disclaimer

This report contains a technology scan intended to provide CURE Afvalbeheer a general insight in the information provided by REnescience and Dong about the REnescience process, which CURE considers to acquire.

CE Delft hereby emphasises that this report is not a due diligence study and is not intended to support any investment decision, but to give an opinion on the set of data provided by the supplier/partner REnescience. An investment decision requires a full study on all available data, both technical as well as financially in a next phase.
This report relies on the correctness of data as provided by REnescience, Dong and third parties, and gives an expert view on it. And, where reasonably possible, the data is checked for inconsistencies, but not on completeness (REnescience and Dong did not provide all data requested by CE Delft).
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Remarks on the project execution
Although CE Delft has ample experience in the calculation of technical projects and preparation of business cases, we cannot be considered an engineering firm nor financial consultancy. There is sufficient business economical expertise available, but we do not offer advice on legally required administrative requirements, (detailed) valuations, nor tax rules.
Thus, this document provides a general view on the REnescience technology, future expectations on the applicability for CURE including currently existing uncertainties.

Preface

CURE Afvalbeheer is a waste management and services company fully owned by municipalities in the region of Eindhoven. In its role CURE has the ambition to apply the latest technology in reaching it's goals on sustainable waste recycling. By choosing for the REnescience process of Dong Energy it strives on matching or exceeding the number one technology for post collection waste separation in the Netherlands of Dutch colleague waste company Omrin (and Attero).

This report is a technical review of the REnescience process. It comprises the following aspects:

- Waste input definition
- Pre-treatment
- Added materials / enzymes
- Process window and –control
- Process robustness and inhibition
- Product output and -quality
- Cost aspects and –sensitivities
- Energy
- Directions for further innovation

The results offer CURE insight in the process performance and sensitivities, which information can be used as input for risk management and risk mitigation prior to the realisation of the project.

Also, it show opportunities for further innovation after the realisation of the full scale process.

In addition to the in-house expertise of CE Delft, three experts in the field have been interviewed on their views in relation to the REnescience process.

Contents

Summary

The REnescience process of Dong experienced a pilot stage of several years running on municipal waste mainly from the Copenhagen area. This pilot unit reportedly demonstrated the successful conversion of the biomass fraction in the waste by dosage of an enzyme mix, which results in selective enzymatic degradation of the biomass, except for the woody lignocellulose fraction. Successively, this biomass is converted in a bio-liquid, which is easily converted into bio-gas, intended for purification into grid quality methane.

Mainly, 2D plastics (foils), 3D-plastics (i.e. bottles), fibres, inorganic materials etc. remain as a solid material and are treated in mechanical separators.

While many enzymatic degradation reactions will occur in a highly complex serial and parallel manner, the process is based on a trial and error approach by over dosage of enzymes. This likely will provide room for improvement during operation.

While possible inhibition of the enzymatic degradation is unknown and reportedly not observed in the trials executed in Copenhagen, it is eminent that a representable waste sample from CURE Afvalbeheer is properly tested under controlled steady-state conditions. By assessment of the quality and quantity of the produced gas-, 2D and 3D plastic- and residual fractions it will enable CURE Afvalbeheer to obtain a clear picture on the applicability on its waste type and on the profitability of the business case for CURE Afvalbeheer.

Details on the approach of the upscaling of the process to full scale reactors, including process control, are currently unknown, but also play an important role in the future success of the process at CURE Afvalbeheer, therefore need to be reviewed.

1 Introduction

1.1 Vision and approach

CURE Afvalbeheer strives in becoming the most sustainable waste company in The Netherlands. By choosing for the REnescience process of Dong Energy it expects to realise this ambition. DTU has performed a screening LCA, which was reviewed by CE Delft and reported [G. Bergsma, Screening LCA review, Final version Delft, April 2015]. This confirmed this ambition and resulted in the conclusion that this process is at least as sustainable as the best process in The Netherlands of Omrin. The innovative REnescience process still poses room for improvement, while the Omrin process was already optimised for years after its realisation, so the outlook is that the REnescience process can indeed become the leading technology in The Netherlands if the foreseen improvements can be implemented.

The current state of development of the REnescience process is a 1.200 kg/hour demonstration plant running from 2009 on mixed domestic waste originating from tube waste systems of apartment buildings from the Copenhagen area using small plastic bags. Based on the positive findings with this plant REnescience plans to upscale it with the help of Dong to 80,000 to 120,000 ton per annum scale with CURE as one of its launching customers.

CURE plans to have a 120,000 ton/annum realised by Dong in the Eindhoven area. The capacity of a 120,000 ton/annum unit is to be topped up with waste from nearby communities. Furthermore CURE prefers to take a 50^{+} % share in the plant for fully receiving the financial benefits from it resulting in reduced waste fees for its citizens.

1.2 The REnescience process

The REnescience process has been developed by Dong Energy (the major Danish utility). The description of the process in this paragraph is based on the information provided by Dong, directly and via Nowit. It comprises of 2 main process sections:

1. Selective enzymatic degradation of biomass in two rotating tubular reactors. Here, the biomass fraction is converted into a bio-liquid by use of enzymes and bacterial action and therewith separating it from the remaining solid phase comprising 2D / 3D plastics, fibrous / woody material and inert fractions.

2. Solid residual material is separated into 2D and 3D plastic, fibre and inorganic material fractions

In essence the first step of section 1 has a double action: besides biomass conversion it also enables readily separation of the degradable biomass from the rest of the residual solid materials.

The schematic Process Flow Diagram (PFD) of the current demonstration plant under review is shown in figure 1:

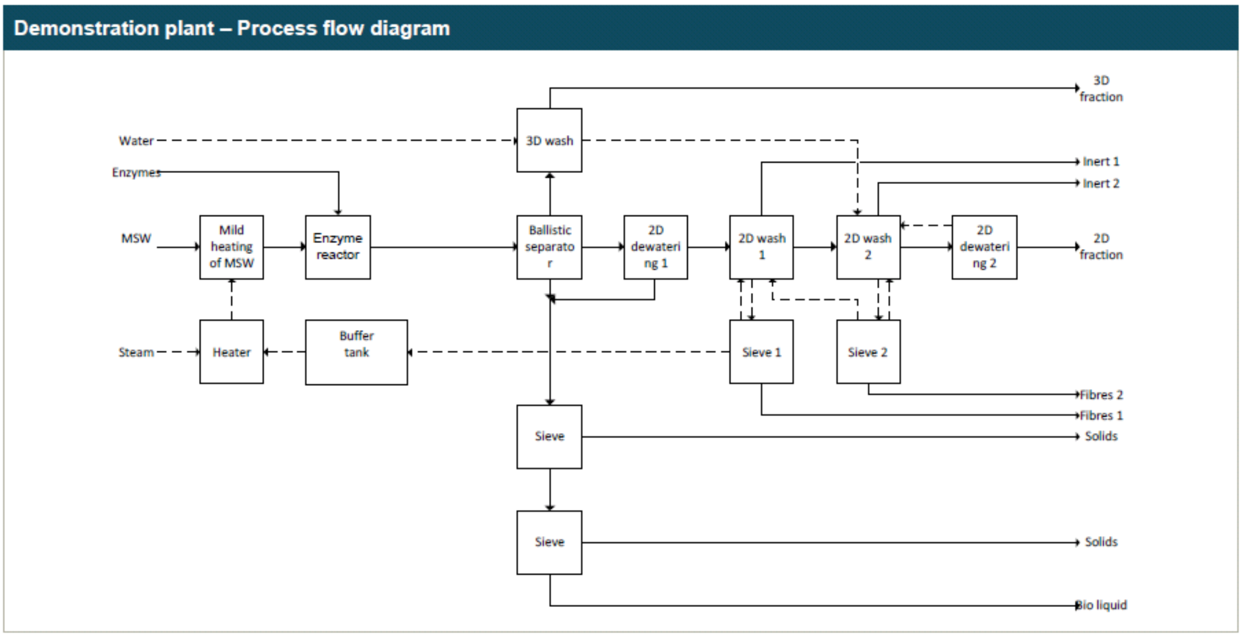


Figure 1. Schematic *process flow diagram (PFD) of Copenhagen demonstration plant.*

In more detail the current demonstration plant comprises of:

1. Heating of MSW with added warm water
2. Addition of enzymes
3. Enzymatic degradation in first reactor
4. Further bio-conversion in the second reactor
   into free sugars and organic acids
5. Separation, sieving and dewatering of bio-liquid and solid fractions
6. Water recovery for recycling and reheating

The full scale plant planned for CURE includes an anaerobic digestion plant, evaporator and gas clean up to produce green gas from the bio-liquid. The simplified flow diagram with partial mass and energy balances for use as input for the business case, is shown in figure 2:

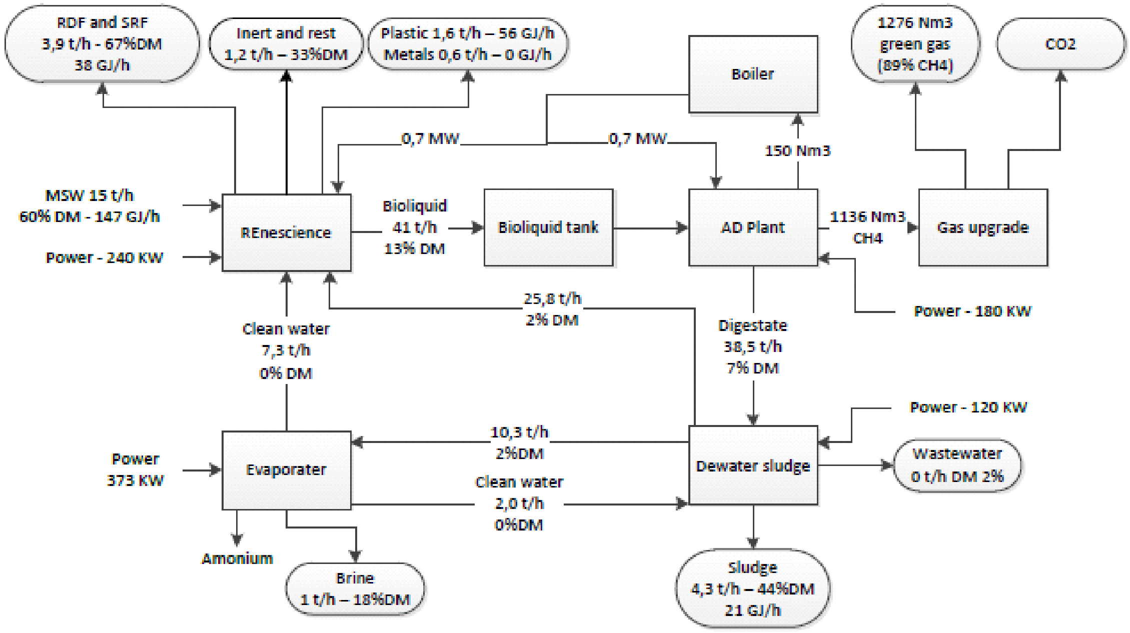


Figure 2: Simplified flow diagram of full scale plant with anaerobic digester (AD) plant for CURE.

1.3 Input waste composition from the Copenhagen area

Based on the confidential information provided by mail of February 16th 2015 from Dong via Nowit [Data for DTU, REnescience LCA input, report, RSC-Tech LCA Data to DTU report.docm] the following pie chart of the tested waste composition from Copenhagen area can be given, see figure 3:

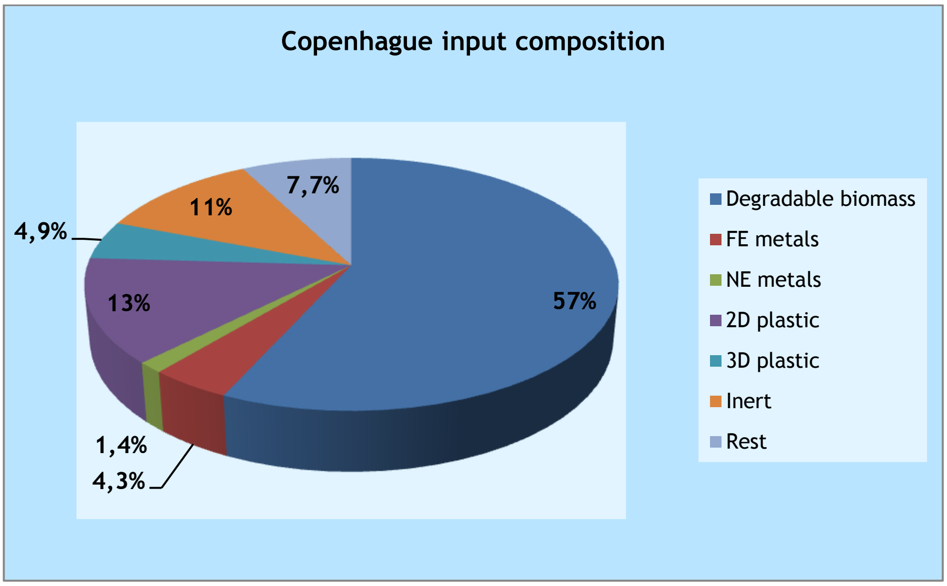


Figure 3. Input waste composition from Copenhagen area.

These data are used as the starting point of the conversion and separation performance of the REnescience process. However, they should be treated with great care, while waste composition data tend to vary substantially over time under real life practical conditions.

1.4 Enzymatic conversion and separation

Of the input composition mentioned in the previous paragraph, the enzymatic process converts part of the degradable biomass, while the rest of this biomass ends up in the other solid fractions.

Of the solid fractions most material ends up in the right solid fraction, but smaller parts get into the bio-liquid and other fractions. This is depicted in the following graphs of figures 4 and 5:

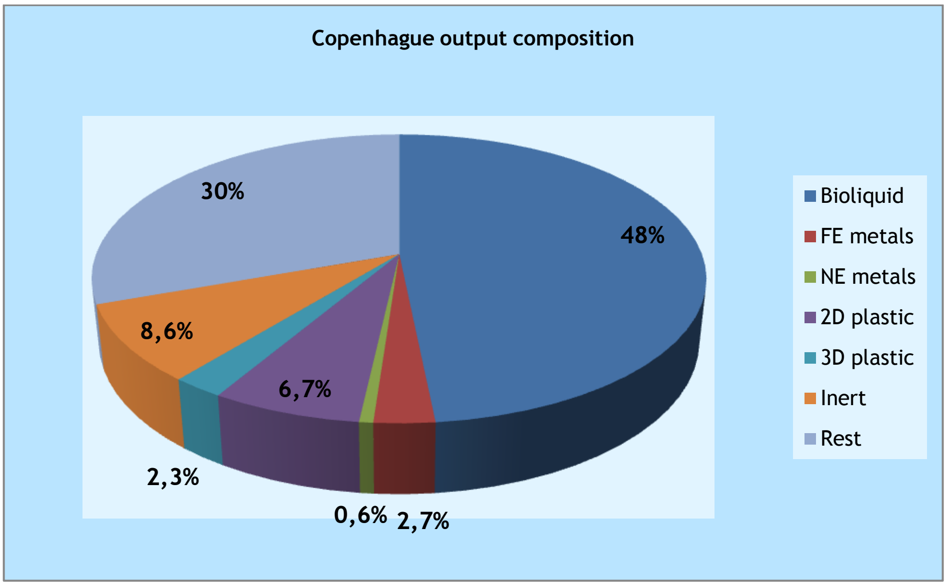


Figure 4. REnescience output composition from Copenhagen area waste.

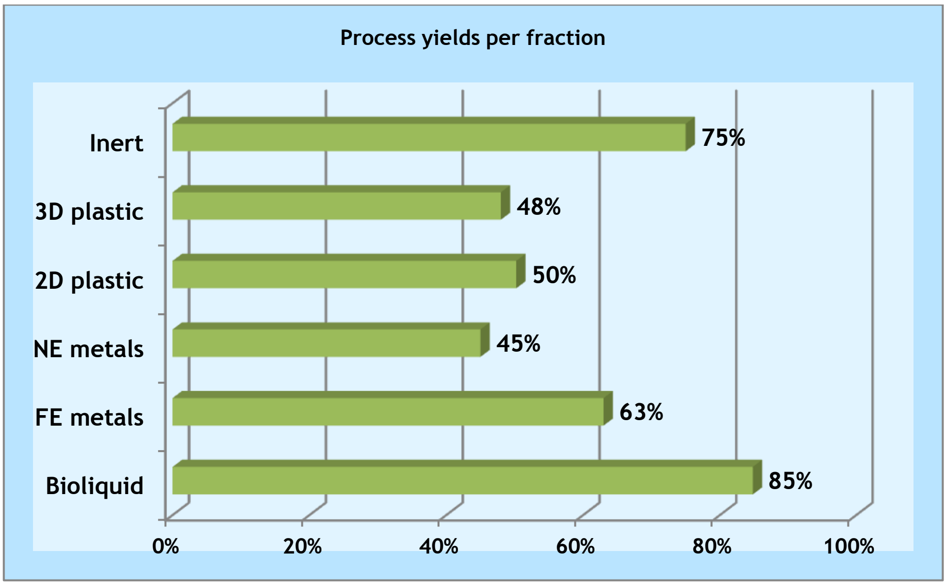


Figure 5. REnescience process yields from Copenhagen area waste.

It is clear that the REnescience process gives the best yield on degradable biomass of 85% (wood and fibres are not converted) and other solid fractions show fair to good recovery percentages.

Although municipal solid waste (MSW) of Denmark will show similarities with the waste from the Eindhoven region of CURE, it is likely that some differences in composition will occur i.e. in garden waste. The results of the comparison between the sorting tests of the two will become available in a later stage. Initial numbers used for modelling of the future CURE plant are given in the following table 1:

Cure – Municipal Solid Waste composition

Main category	Sub-category	[%]
Paper/cardboard		20.0%
	Paper other	16.5%
	Beverage cartons	3.5%
Organic		36.0%
Metals		4.5%
	Ferrous	3.4%
	Non-ferrous	1.1%
Plastics		14.6%
	Packaging	10.26%
	Pet	*1.93%*
	PP	*1.64%*
	HDPE	*0.79%*
	LDPE	*2.89%*
	Mix unwanted	*3.00%*
	Non-packaging	4.30%
	PET	*0.35%*
	PP	*1.49%*
	HDPE	*0.52%*
	LDPE	*0.70%*
	Mix unwanted	*1.24%*
Other		24.9%

Table 1. Initial CURE waste composition used for modelling by Dong.

This initial composition table shows a similar total bio-degradable fraction but with 10,26% a lower fraction plastics than Copenhagen (13%).

Therefore, the general yield numbers on input fractions has been requested and provided by Dong/Nowit, see table 2.

Output fraction	Yield	Yield per ton of waste input	Remarks
Bio-liquid	90% of bio degradable material		
3D plastics	65% of 3D input		
2D plastics	65% of 2D input		
RDF		25% / 250 kg	LHV: ≈ 8-12 GJ/ton
Biogas	31 Nm^3 CH4/m^3 Bio-liquid	85 Nm^3 of CH4	
Digestate		28% / 21% on dry matter basis	LHV: ≈ 5-6 GJ/ton
Brine		7% (≈ 2% on a dry matter basis	

1.5 Deviations from enzymatic conversion

The enzymatic degradation process is based on the natural process of enzymatic degradation i.e. as used by fungi. In nature it is a quite complex set of parallel reactions of which the products can result in both acceleration as well as inhibition. Thus, if a certain composition works well with a specific mix of enzymes this is today a process of trial and error. [quote of interview with prof. R. de Vries, CBS Fungal Biodiversity Centre, Utrecht, The Netherlands].

For the REnescience process of Dong it is claimed that a stable conversion over years with different mixes of enzymes and waste compositions was shown at different settings, but data on these differences was not revealed, only general performance data for Copenhagen waste.

In principle inhibition of enzyme reactions will occur. For instance fractions of (ligno-) cellulose (from GFT/wood) are able to adsorb enzymes, thus taking them away from enzymatic action in the reaction zone. But in the Copenhagen practice this was probably overcome by application of an overdose of enzymes. Another reason is that Copenhagen waste has no/small amounts of GFT, while CURE waste can and will comprise this fraction. This emphasises the need for thorough actual testing with real waste feeds from CURE.

Limiting of these inhibiting (ligno-)cellulose fractions in the feed will give room for improvement in reduction of the enzyme dosage, reducing cost and further improving LCA. To control this, a proper analysis of the enzymatic activity is advised in order to dose the enzymes more exactly.
Development of such a control loop can also be part of the innovation program after realisation of the full scale unit for CURE.

For the full interview please refer to the Appendix.

1.6 Qualitative aspects of the 3D-plastics

During the enzymatic and biological processes in the reaction zones the plastics are in direct contact with the bio-liquid under elevated temperature. This will have effect on the nature of the plastics, while in the presence of this type of organic acids a coating can be formed.
[quote from interview with prof. P. Rem, head of Resources and Recycling, TU Delft, The Netherlands]

Additionally, the bio-liquid will result in an odour, making these 3-D plastics unsuited for food and other high value applications. This will result in a lower market price for these recycled 3-D fractions. Care should be taken in selecting the right market value for the resulting 3D-fraction in the business case. It is advice to produce a 3-D plastic fraction from CURE waste in the Copenhagen pilot plant and use it for evaluating its actual market value with market parties in The Netherlands.

This 3-D quality issue could be tackled with an extra process removing the coating and/or odour, but this will add cost. More information can be obtained in an additional study based on the to be produced 3D- test fractions.

For the full interview please refer to the Appendix.

1.7 Production of bio-gas in an anaerobic digester

The bio-liquid produced in the REnescience will firstly be used for conversion into biogas and cleaned for introduction in the local natural gas-grid. In a later stage it is considered to use it as a basis for bio-based chemicals, i.e. organic acids and free sugars.

While the composition of the bio-liquid from the CURE waste is not known, an exact outlook on the production of biogas cannot be given.

Thus, based on the Copenhagen waste a yield of bio-gas per unit of bio-liquid was obtained [ref. RSC-Cure-NL - Response to requests for information, Doc. no. 2183734A of REnescience-Dong]:

- 55-60% of dry matter (DM) ends up in the bio-liquid
- 85 Nm3 of CH_4 is produced per ton feedstock waste
- An (undefined?) amount is used for heating of the water/liquid

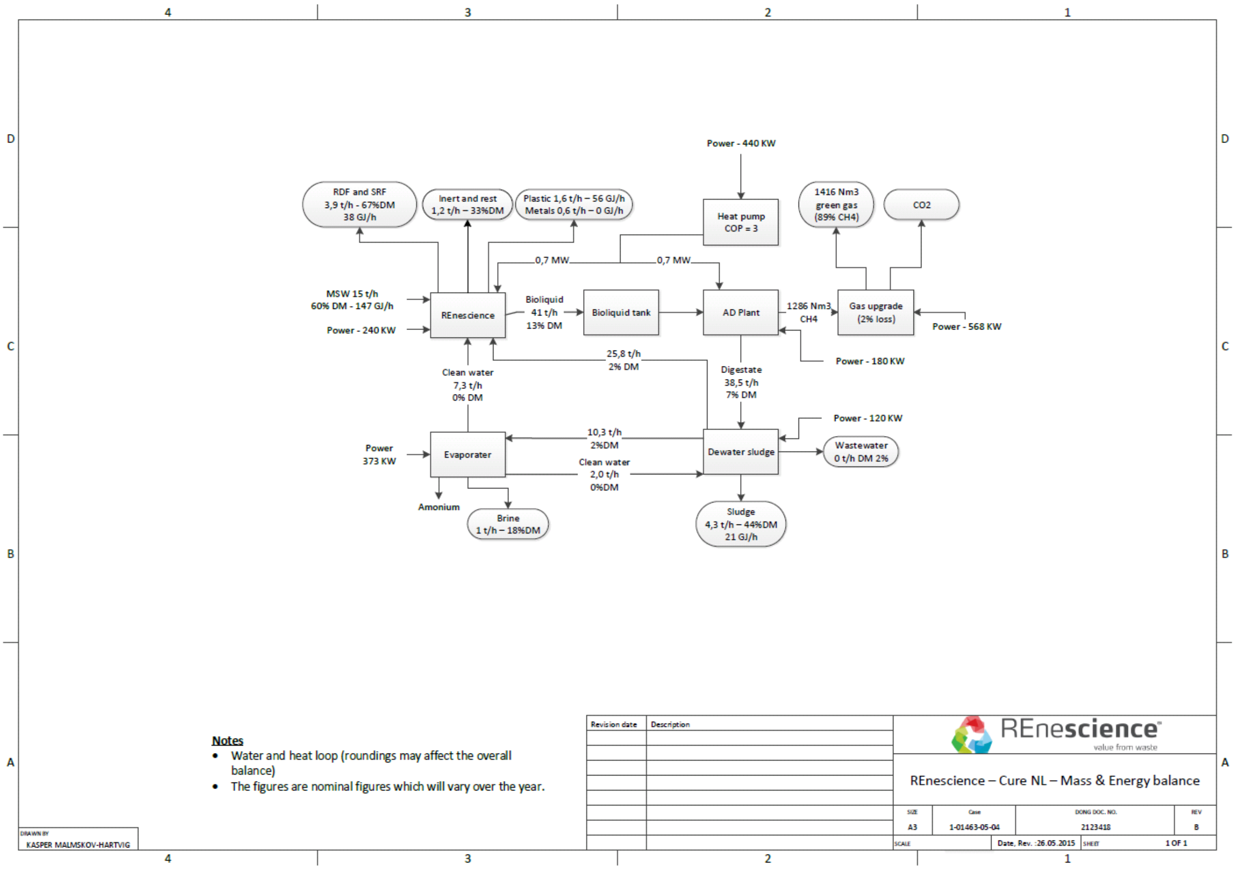
As reported in the report of G. Bergsma a 2x larger amount of gas per ton of waste than Omrin can be explained by the following factors:

- all biomass containing waste is treated, not only the part separated into ONF (7% for Attero);
- also paper is treated;
- application of enzymes lead to free sugars and acids, which are more easily and effectively converted into bio-gas.

No general data on the anaerobic digester type, which will be realised in the full scale unit for CURE were available yet for this report.

1.8 Mass- and heat balances

The review of the simplified mass-and energy balance is based on revision B of document no. 2123418 of REnescience-DONG received via NOWIT:



Dong indicated that it is not an exact version of the PFD, but indicates the main flows of the process, which are relevant for the business case (e.g. the CO_2 and ammonium flows are not included).
Additionally, it is based on one setting, other settings i.e. changed water flows will result in deviations from the values resulting in new mass and energy balances.

Besides this, the mass balance shows fair equilibrium of the mass flows. During optimisation it is likely the mass balance will change and needs to be evaluated before execution.

The energy balance shows significant 1,9 MW_e electrical input of which part is converted into about 1,7 MW_{th} thermal input. The latter is mainly used for heating of large volumes of process water, which heat is partly recycled.
In the REnescience reactor section the recycled water and water from the evaporator return at approximately 50 °C, at the same level as the reactor temperature. The REnescience reactor section will consume about 700 kW_{th}, which is fed via heating of added water, to heat the total of water and waste input to 50 °C. This power value is based on the heat capacity (C_p) of water and reportedly in line with the pilot tests in Copenhagen. This can be confirmed with the CURE waste during the planned pilot tests to support the upscaling.

2 Conclusions

The REnescience process of Dong has been extensively tested over several years in a pilot-plant in Copenhagen. It showed a ready conversion of a large fraction of the wide range of biomass present in the MSW from the Copenhagen area into a bio-liquid. The ligno-cellulose fraction, i.e. in wood and fibres, is not converted. The remaining 2-D and 3-D plastic fraction and inorganic materials could be sorted with a reasonable efficiency. For the bio-liquid good bio-degradability in an anaerobic digester was claimed, showing ample bio-gas production intended for methane feeding in a gas grid.

For the conversion of specific waste of CURE, which is to be used in a 120,000 ton/year full scale plant the following aspects are to be confirmed in actual testing:

We advise to validate in a witness test and/or address:

- The overall performance with real representative CURE waste in the Copenhagen pilot-plant
- Confirmation of market values based on actual CURE waste i.e. on quality and market value of 3-D plastics by actual testing of sample material. This should result in value predictions by several plastic recycling companies in the Netherlands supporting the business case values.
- The route to upscaling, process modelling including inhibition
- Process analysis, process control and enzyme optimisation

A lot of data was given and questions properly answered, which did not show clear inconsistencies. However, not all data was known or revealed for this study i.e. inhibition effects, plastic quality and process data using different settings and/or other different waste feeds.

Although no specific issues are identified, the upscaling and engineering should be carefully executed, mitigating all known risks, in order to obtain a first successful full scale waste conversion plant. This can be reached by a engineering of a full scale design with added redundancy and ample measurement and control. The planned multiple reactor approach is a good first step in this.

Additional heat recovery based on an energy PINCH analysis can provide further opportunities in savings of the energy consumption. And a (bio-) CHP may be considered, because of the reasonably well matching ratio of large amounts of self consumed heat and power.

On the long term thermal conversion or gasification of the 2D plastics and RDF waste streams may provide an on-site solution and reduce the residual waste output and increase energy efficiency.

Annex A Expert interviews

General issues waste conversion process - REnescience/Dong
Interviewed: prof. Peter Rem
By: Diederik Jaspers
Date: 17-3-2015

Question	Answer
1. How do you see the market of post-collection waste conversion in relation to separation at the source and existing recycling targets?	For source separation still a low tech approach exists, while it dpends on collaboration of people, which is most affected by a feeling of usefulness. Then a 70% response is viable. A more advanced approached is single pick-up of mix of bagged fraction identified with a barcode label connected to type and source address, enabling feedback. Then hand-picking is economic also in Western countries. Collection of textile waste material is attractive due to € 0,5/kg prices and also spent batteries. Post-collection of waste can become the 'perfect solution'. A lot of interesting pathways are to be explored and tested. Extraction of clean organic fractions i.e. for recovery of pure proteins has good potential, including from insects. Future simple distributed waste conversion units producing several pure fraction would be optimal.
2. What processes do you see applicable for this new market?	Steiner IR spectrum based separators, magneto hydro-separation.
3. How does this process of enzymatic conversion and separation fit in this?	Very good, the combination of conversion process for the organic fraction and separation of 3D and 2D plastics into clean fractions is a strong one.
4. What are advantages, disadvantages, and critical issues to be met (CSF's)?	Disadvantage is the that the project relies on government subsidy for the bio-gas.
5. What are the expected economics?	Good when then enzyme dose can be limited and is not too expensive and by the sale of 3D recycled fraction. Economic value of the products should be added to future criteria of the LCA. Additionally, in the future the plastics industry should stick to few standards for a specific product, greatly improving recycling economics. Thermal conversion of the 2D fraction i.e. with hydro-pyrolysis could be a good fit.
6. Do you see this method as feed for bio-digestion as a proper use of low quality biomass?	Not optimal, but acceptable if structural government support is present (on the long term this could become uncertain).
7. How feasible would be the future use of the bio-liquid for bio-based chemicals?	Recovery of proteins and sugars i.e. for bio-alcohols would be more interesting for the business case, but this needs development.

8. Do you expect issues with policy, law and permits?	Not particular. There is a policy shift at ministry of I&M towards more technological solutions and innovations, not only 'Lansink hierarchy' leading but market prices of produced fractions. Biohazard: Peter Rem is very surprised that bacteria are present in the presence of the enzymes. Similar to other processes, produced fractions require sterilisation before storage and sale.

Additional remark: incinerator residues contain ample metallic aluminium particles. These can readily be converted into hydrogen gas.

General issues waste conversion process - REnescience/Dong

Interviewed: Mr. H. Huisman, RWS 06-51175992
By: Diederik Jaspers
Date: 30/3/2015

Question	Answer
1. How do you see the market of post-collection waste conversion in relation to separation at the source and existing recycling targets?	The quality of the post collection separation of plastic bottles is the determining step. In many communities already fair recycling good recycling percentages of 50% exist, in other this is only 25% (Roteb Rotterdam), Additional post collection separation can be applied. Amsterdam applies post collection separastion plus anaerobic digestion (Omrin SVI) which results in a bonus by less incineration (question: does this account for in the LCA?). For large Dutch cities, like Eindhoven, with less source separation post collection separation is a well suited option. Beware not to convert the bio-gas in a CHP; feed-in of methane in the gas grid is preferred. Smaller Dutch cities like Nijmegen, Apeldoorn using Diftar (system of variable waste levy) do have good source separation performance. Cities like Amsterdam, Rotterdam (and propbably Eindhoven?) perform worse. OVAM in Flaunders performs at 71% source separation with a Diftar system. Local Belgian communities receive their subsidies based on a system, which partly depends on environmental- and waste recycling performance. The Dutch convenant on packaging materials is focused on avoidance of double packaging, but contrary to this, laminated packaging is entering the market, which is difficult to recycle.
2. What processes do you see applicable for this new market?	The Omrin proces, hyperbaric pressing using a VM press, anaerobic digestion of organic fractions, sorting of dry fractions and separation into energetic RDF has become commercial in Germany. In countries like India this is of interest duet o the large wet organic fraction. In Shenzen, China WTE 2012 incinerator system with 2 waste bunkers comprising circulated percolate with >60% organic fraction. After 3-5 days an increased a higher caloric value is obtained for the thee WTE incinerator plant.
3. How does this process of enzymatic conversion and separation fit in this?	• Digestate from the process can only be used in agriculture when using certified 'clean biomass' as a feed, which is not the case here Digestate from the anearobic digester will

	encounter similar limitation and needs tob e confirmed beforehand. • Small inorganic residues can only be used as filler material for road construction when clean, so needs to be checked. Furthermore there is ample supply of similar filler material from dredging of Dutch river low lands, so currently will be difficult. • Projects based on non-structural single subsidies are risky. Only projects based on structural subsidy programs like the Dutch SDE^{+} over ten years are OK. • What possible inhibitors can disturb the process performance? • Organic acids could reduce the quality of 3D plastics by deposition of an oily layer. And the uptake of smell can be problematic for PET bottle recycling with a food application.
4. What are advantages, disadvantages, and critical issues to be met (CSF's)?	The quality of the 3D plastics should not be reduced in the Dong-REnescience process including smell (plastic etching process is commercially offered by a US company to restore this) According to prof. Rem the nature of the plastic packaging materials will change in time by the introduction of thin walled laminated foils instead of the current thick walled non-laminated versions. The laminated versions are worse in recycling but the positive effect of increased product quality outweighs this effect in the LCA (Nedvang).
5. What are the expected economics?	The Dong-REnescience process should be able to compete with existing systems, non-subsidy driven and applicable in larger cities.
6. Do you see this method as feed for bio-digestion as a proper use of low quality biomass?	As an addition to source separation and limited to those parts of cities, where source separation is not sufficiently effective, so fine.
7. How feasible would be the future use of the bio-liquid for bio-based chemicals?	There is already a development on source separated chemicals (by TNO, de Boo) and Wageningen In the lab fantastic results, but there is a long way (ten year) to go in development of this, starting in feed sector. Pharma even longer due to regulations. This in the light that the well developed anaerobic digestion is today still at only a fair level.
8. Do you expect issues with policy, law and permits?	Already strong demands for waste and units of smell. eisen voor afval / geureenheden. If they are met , fine. Example: an process for recovery of proteins from blck fly maggots had a problem with the slaughter permit

Additioanl remarks:

- Dutch policy: 75% recycling target, 25% to an incinerator with R1 efficiency.
- There is innovation in the area of the LCA calculation method by his colleague Kraakman a.o.

General issues waste conversion process – REnescience/Dong
Interviewed: prof. de Vries
By: Diederik Jaspers
Date: 19-5-2015
General: during the visit a large group of Danish DTU students visited the CBS group of prof. de Vries.

Question	**Answer**
1. How do you see the market of post-collection waste conversion in relation to separation at the source and existing recycling targets?	<Not in his domain> Remark: a robust system is preferred. This in the light of strikes in the city of Utrecht which caused major problems.
2. What processes do you see applicable for this new market?	Bio chemicals and biomaterials synthesis, but also composting products e.g. substrate material for mushroom production.
3. How does this process of enzymatic conversion and separation fit in this?	Enzymatic degradation of biomass by enzymes from fungi is a very efficient and potent process, while based on long natural evolution. However, basic scientific understanding of such a process as REnescience-Dong is lacking, while even the basic enzymatic processes in nature are highly complex and very much interlinked. This type of processes is based on trial-and-error with existing commercial enzymes, which are developed for other purposes. Thus, there is a lot to gain when specific enzymes are developed. Sequence of different enzymatic reaction is also an important factor, while some have an inhibiting effect on the starting reactions. Therefore thorough understanding of the combinational performance between enzymes is an important pathway for research and largely unexplored. E.g. the natural degradation of lignocellulose is a hot topic. Conclusion: biomass waste degradation of this process is certainly achievable, but further development firstly requires 'three steps back' to obtain fundamental understanding in order to make the big leap forward. The R&D political climate in The Netherlands may not be optimal for bio based, so partnering with other countries like Germany and Denmark were this is better. DSM was also mentioned.
4. What are advantages, disadvantages, and critical issues to be met (CSF's)?	Sustainability is considered a true advantage. Remark that waste situation can change in time by government policy to reduce the generation of waste, which may affect the practical implementation of the process. Policies of different Dutch ministries can be competing resulting in an uncertain outcome in regulation (policy of less waste vs better waste for use in circular economy or product quality/shelve life). During 10-15 year of complete

	development to bio based materials the world / waste supply / market demand can change.
5. What are the expected economics?	Certainly good, but optimisation requires a lot of development work, while it requires knowledge of fundamentals of the process.
6. Do you see this method as feed for bio-digestion as a proper use of low quality biomass?	Digestion to produce biogas is certainly a proper way to produce value on the short term. Additionally it makes it for public acceptance easier to understand (bio based chemicals is a too complex message)
7. How feasible would be the future use of the bio-liquid for bio-based chemicals?	This largely depends on the energy of separation and purification and FTE required, while this affects the LCA. (these can be very expensive and carbon intensive). Beware of residual components from medicine emissions. Than these are realistic options. Apart from free sugars and organic acids, citric acid is a product which is very efficiently produced by the metabolism of fungi. Development of bio based chemicals takes in the order of 10 years.
8. Do you expect issues with policy, law and permits?	Beware of negative stories in the press. Largest risk is false information on GMO, so preferably apply GMO free feeds. The Netherlands public opinion can be very focused on negative news and blind for positive success stories.

Additional remarks and advice:

1) Preferably, a biobased innovation project contains partners which can help in the identification of the best possible and marketable products for the process
Example: focus can be on maximum production of free C5 sugar production suppressing it's conversion and organic acids production or the reverse. This selection is governed by the sensitivity caused by fluctuations in the waste composition.
Note: by chance the department of CBS already tested a fungus, which does not use the free sugar for its metabolism (this was turned off) enabling its production. But under practical conditions with biomass, this did not work anymore and further research is required.
Finding the proper mix of enzymes (from fungi) which supplies synergy between the parallel enzymatic reactions will give ample gains. Finally, a partner who enables the uptake towards the process engineering can prove very valuable (different disciplines).

2) Harvest ample bio-liquid sample for evaluation of the mix of free sugar and organic acid levels during the witnessed test on CURE waste (and store properly).

3) Inhibition of enzymatic degradation is an issue. Low or high pH, molar concentration (salts and materials), inhibition by (by-)products, enzyme adsorption on plastics, cells and lignocellulose. A > 50% enzyme loss due to adsorption can be expected!

4) Quick testing and probably in-line measurement of enzyme activity is possible with commercially available analysis kits and/or equipment. This helps in the fine tuning of the enzyme dosage limiting its use resulting in cost reduction and improved LCA performance. Develop process control based on the dose-response characteristics.

Annex B Information received from REnescience/Dong

Reports	
Environmental Performance of REnescience in the Netherlands LCA screening, October 30th, 2014	DTU Environment Davide Tonini Roberto Turconi Thomas Fruergaard Astrup
Data for DTU, REnescience LCA input Confidential	-
RSC-Cure-NL Response to information request 24 April 2015, doc./version 2183734A	Kasper Malmskov-Hartvig (KAMAL),

Subject	LCA screening: Questions from the Netherlands for DTU
To	DTU Miljø (Thomas Astrup, Roberto Turconi, Davide Tonini)
Copy	
From	Thomas Krüger
Regarding	Comments/questions for the LCA screening

Hi Roberto,
The following questions/comments for the Dutch LCA screening for Renescience have been received. Could you please provide your comments/answers?
BR Thomas Krüger

Reply from DTU in blue

Doubts/questions per page?

1. Page 7: CHP with 40% net electricity efficiency and 50% heat efficiency seems very optimistic. This is a large CHP plant with a good contract for the heat with low temperature (no seasonal variations in demand)

   The values correspond to a new small gas engine which can reach 88-96% net total efficiency and 40-48% electricity efficiency (Energi Styrelsen & Energinet.dk, 2012, page 54), and we considered optimal positioning of the plant (thus high heat recovery). This is consistent with the state-of-the-art assumption for the Dutch MSWI plant (see question 7). Seasonal variations in heat demand were not taken into consideration, as they will depend on local conditions (e.g. whether heat is used for heating or for an industrial process). In a full LCA study (rather than a screening), these aspects could be implemented based on detailed data on the local market for heat.

2. Page 9: Natural gas fired power plant is seen as marginal technology (reference 2011). Because of the high gas prices this is much more complex in the current Dutch electricity market. The amount of coal has gone up. We suggest to use a mix of gas and coal or to use the figures provided by the government. (RENEWABLE ENERGY MONITORING PROTOCOL, Update 2010[1])

   We acknowledge that the choice of the marginal can be debated. Identifying marginal technologies is a challenging task, even more so for electricity, due to the complexity of the market and the influence of renewable energy policies. Ideally, the choice should be based on a large consensus between all stakeholders involved in the study, as different approaches are available for identifying the marginal electricity of a system.

   We followed historical trends, as suggested by Schmidt et al (2011) and Turconi et al (2011): natural gas was chosen as the marginal as it is the most fluctuating source (varying over time) (Figure 1). Further investigations on this topic is clearly a priority, as it was pointed out in the “goal and scope definition” and “limitations and further research” sections.

[1] http://www.rvo.nl/sites/default/files/bijlagen/Renewable%20Energy%20Protocol%20Monitoring%202010%20DEN.pdf

However, please note that if coal was the marginal for electricity, then the waste refinery scenarios involving CHP production (Assessment 2, see Table 5 or Figure 13 at page 25) would be even more beneficial than incineration (scenario 1) as it stands now. This is because: (i) the waste refinery scenarios generate more electricity and (ii) the GHG emission factor of coal is about 1.7 that of natural gas (1100 g CO_2-eq./kWh_{el} vs 643 g CO_2-eq./kWh_{el} for natural gas).

Regarding the suggested document from the Dutch government: as we are performing consequential LCA we should focus on the marginal electricity source, i.e. the technology likely to respond with a change in production as a consequence of a change in demand. The emission factors provided in the document (Table 3.3 and Table F1) are not applicable, because they refer to the average electricity production in the Netherlands rather than the marginal source. See (Ekvall & Weidema, 2004) for further information on consequential LCA approach and choice of marginal technologies.

3. Page 10: The marginal technology for heat is gas based district heating with an efficiency of 90%. This is not correct for the Dutch situation where district heating has only a small market share. A High efficiency gas powered installation should be the reference with an efficiency of 107% (see also the monitoring protocol)

   As mentioned in the text, we acknowledge that the heat demand is strictly related to local conditions. Again, a more detailed modelling could be performed based on more detailed data on the local heat market. This should not be average data, but rather data associated with the responding plants in the local market (local area) where the technology would be established.

4. Page 10: Loss in recycling: The loss in recycling mainly by energy use in the Dutch plastic recycling system seems higher than the assumption here of 10% (in general 50%)

   We are not sure what a 50% "loss in recycling mainly by energy use in the Dutch plastic recycling system" refers to.

   The value reported (10%) refers to the loss in quality of the plastic after recycling (e.g. polymer cross-contamination, degradation, etc.), not to the energy use. Energy use at the recycling plant is accounted for in the recycling process (i.e. through the consumption of electricity, 90 kWh/t_{scrap}).

   It should be noted that the total amount of plastic recycled is much lower than the plastic content in the input waste, as the sorting efficiency varies between 26% and 67% depending on the type of plastic.

5. Page 10: Aluminium and copper are more and more separated from Bottom ash. It is not clear if this is in the model. On page 12 AL and Fe are mentioned but Copper is missing.

   Only recovery of Fe and Al was considered. Current inventory data on Copper recovery and recycling are limited, we therefore excluded it from the analysis.

6. Page 11: Is this eco-invent 2.2. Is this different in eco-invent 3.1?

   Ecoinvent v2.2 was the latest available version at the time of the study. In case of a future study (full LCA), we will use the latest version available.

7. Page 12: What is the assumed efficiency of the MSWI installation for electricity and heat. Are this actual Dutch values (the Danish are higher). On page 26 it seem to be 13% electricity and 42% heat, this is different from the Dutch average)

   As explained in the introduction section of the report, the comparison is performed against the AVR incinerator (Rotterdam, efficiency 13% electricity and 42% heat), as suggested by DONG Energy. This is consistent with the consequential LCA approach.

8. Page 14: Why does the digestate burning not result into energy (to wet?)

   Correct. Digestate has very low dry matter content (about 4-6%). Current practice involves mechanical dewatering up to 22-25% total solids, so that the combustion occurs with no energy consumption (net energy balance is zero). This is established practice when combusting digestate.

9. Page 17: For energy the exergy approach is suggested. Why did you not calculate the Cumulative energy Demand (CED) in which electricity is also more valuable than heat.

   The current LCA screening includes GHG emissions and energy balancing, but neither exergy nor CED calculations were included.

   The exergy approach was suggested because it allows evaluation of the efficiency of the waste-to-energy process (i.e. the results do not depend on the marginal electricity and heat chosen). CED calculates the total primary energy demand of electricity and heat consumed or produced, thus the results are dependent on the marginal electricity and heat. Depending on the objective of a specific assessment, both exergy balance and CED method can be useful tools.

10. Page 19: It is suprising that scenario 2 is performing worst. In a CE Delft study an alternative process of Attero with ONF separation and digestion is performing better than an MSWi?

    We do not have information on (i) waste characteristics, (ii) waste management system, (iii) process parameters and (iv) modelling approach, thus we cannot comment on the results of the CE Delft study. There may be good reasons for the differences.

    As stated in the discussion sections, in Assessment 1, waste incineration (scenario 1) outperforms the waste refinery without plastic recovery (scenario 2), as the additional energy consumption of the waste refinery is not compensated by higher energy recovery. In assessment 2, scenario 1 and 2 have similar GHG performance. In both assessments, scenario 2 performs worse than 3 and 4 because plastic is not recovered and recycled, and the fossil carbon of the plastic is emitted as CO_2 after incineration.

11. Page 19: How do scenario 3 and 4 perform if the plastic recycling is resulting in less environmental profit (50% loss in Plastic heroes system)

    This is certainly a good suggestion for a sensitivity analysis in a future study. Sensitivity analysis on key parameters should be part of a full LCA study, thereby evaluating the robustness of the results. Sensitivity analysis was not part of the LCA screening. As you suggested potential areas that could be further investigated are: (i) substituted electricity and heat, (ii) energy efficiency of MSWI and CHP, (iii) plastic recycling. The full list of sensitivity analysis scenarios should be agreed upon by the stakeholders.

First conclusion of the review

The GHG analyses looks like a complete analyses with all relevant aspects in the analyses. The following aspects are missing:

12. The GHG emission for the production of enzymes

This is included in the study, 4.4 kg CO_2-eq/$kg_{enzymes}$

13. The GHG emission for the recycling process for plastics (up to 50% of energy value of the plastic)

Recycling of plastic was credited by substitution of virgin material provision, 1892 gCO_2-eq/kg plastic (Table 2, from Ecoinvent database)

But we have doubts about some data used in the analyses which can be important for the outcome:

14. The efficiency of the MSWI (did you use Dutch averages?)
15. The efficiency of the CHP installation seems high
16. The reference for heat (district heating is not the normal Dutch system)
17. The reference for the marginal electricity. This is not gas any more in the Netherlands. We advise to use the official figures of the Dutch government (mix of coal and gas)
18. It seems that the environmental gain of plastic recycling is rather high (only 10% loss)

The issues raised in points 14-18 have been addresses in the answers to 1-11.

19. Variations, sensitivity analyses could be done for:

- MSWI efficiency
- CHP efficiency
- Plastic recycling system variations

Agreed (see 11).

20. A Cumulative energy Demand (CED) calculation would be interesting for the energy comparison.

Agreed (see 9).

Bibliography

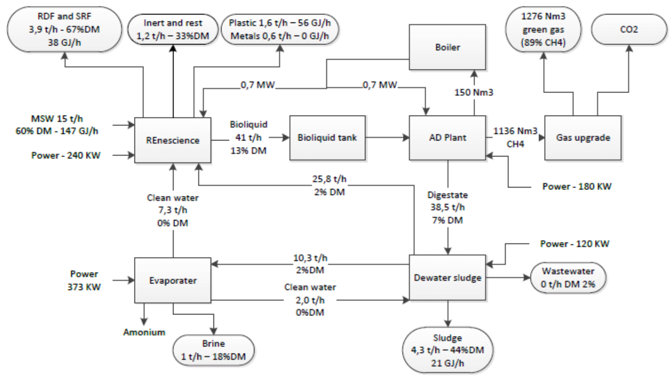
Ekvall, T., & Weidema, B. P. (2004). LCA Methodology System Boundaries and Input Data in Consequential Life Cycle Inventory Analysis, *9*(3), 161–171.

Energi Styrelsen, & Energinet.dk. (2012). *Technology data for energy plants*.

Schmidt, J., Thrane, M., Merciai, S., & Dalgaard, R. (2011). *Inventory of country specific electricity in LCA - consequential and attributional scenarios.* Aalborg.

Turconi, R., Butera, S., Boldrin, A., Grosso, M., Rigamonti, L., & Astrup, T. (2011). Life cycle assessment of waste incineration in Denmark and Italy using two LCA models. *Waste Management & Research*, *29*(10 Suppl), 78–90. doi:10.1177/0734242X11417489

Mass- and energy balance, Revision **A**



Notes

- Water and heat loop (roundings may affect the overall balance)
- The figures are nominal figures which will vary over the year.

DRAWN BY
KASPER MALMSKOV-HARTVIG

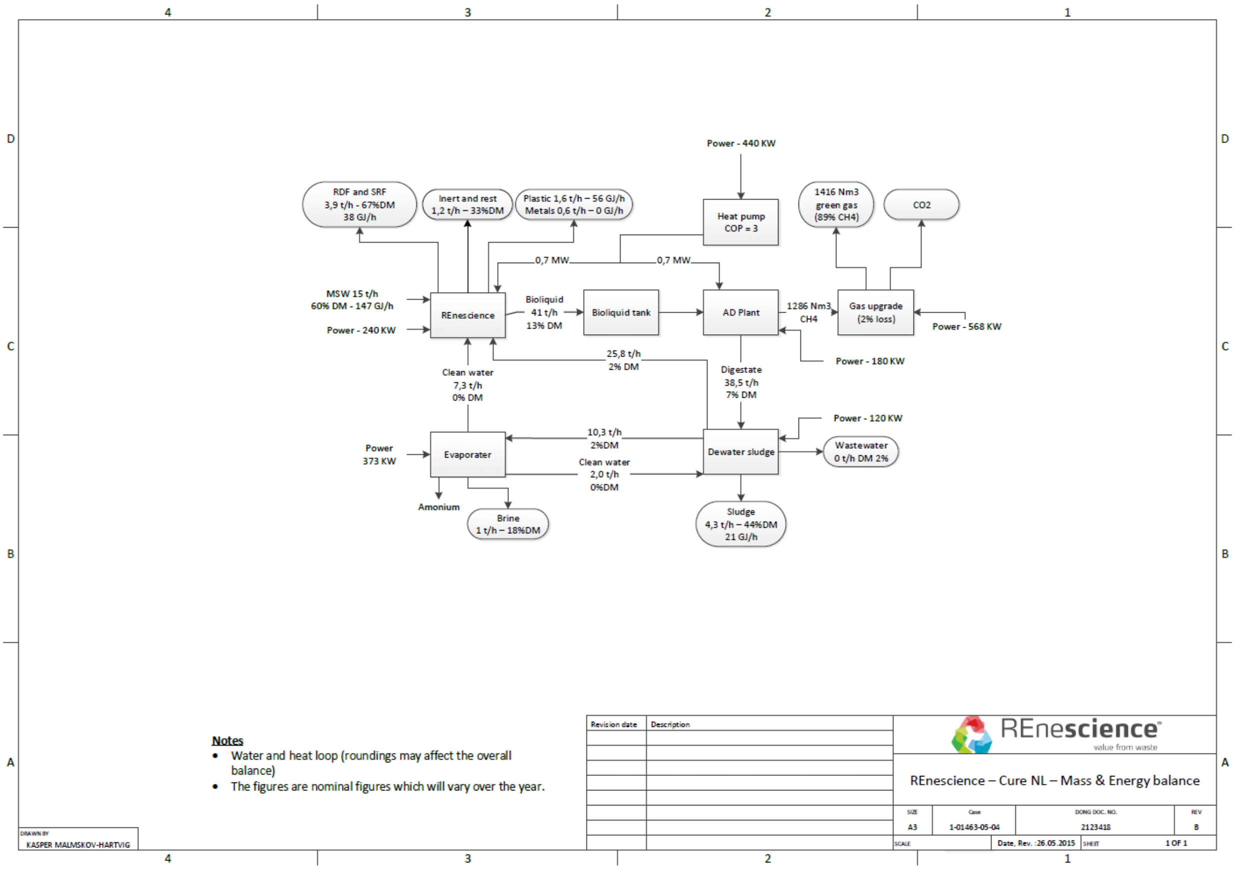
Revision date	Description

REnescience value from waste

REnescience – Cure NL – Mass & Energy balance

SIZE	DOC. NO.	DONG DOC. NO.	REV
A3		2123418	A
SCALE	Date, Rev. :17.12.2014	SHEET	2 OF 3

Mass- and energy balance, Revision B (with heat pump)



Memo

Subject RSC-Cure-NL - Response to 2200061
To Diedrik Jaspers (CE Delft)
Cor Luykx (Cure)
Copy FECAS, ULFAN, PETFI, AHJEN (DONG Energy)
Arie Van Vliet (NoWIT)
From Kasper Malmskov-Hartvig
Regarding Answers to questions regarding doc. 2183734 "RSC-Cure-NL Response to information request"

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18 May 2015

Our ref. KAMAL/KAMAL
Doc. no. 2200065
(ver. no. 2200065A)
Case no. 1-01463-05-04

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Page	Question	Answer
3	And what actions have to be taken to restart the process, how long does this take and what resources are required.	-
3	The results vs settings resulting in the 'process window'.	-
3	and composition	-
3	Unlike to be present in the MSW such that inhibition occurs or at all? (inhibition due to excursions to high/low pH (strong base/acid), amounts of oil-products/grease, biocides etc.)	Unlikely that an inhibition will occur at all. A route to determine the consequence of certain scenarios with substances could be to describe the expected scenarios that can be foreseen and subsequently investigate the effect of those. However as noted the historical data shows no indications of negative performance based on substances and neither have we seen sudden rise and / or drops in pH.

Page	Question	Answer
4	Was Copenhague waste used typical waste from the vacuum system or also more types from waste bins like the case for CURE used? IE inclusion of CURE specific GFT (bio/garden) fractions.	Several types of waste have been processed at our plant in Copenhagen over the entire lifetime of the facility incl. waste collected in the traditional way and waste from other countries outside of DK.
4	Composition buodl-up food-leaves vs wood? (differs in degradation of system)	8% of the organic are garden waste.
5	Calculated as sum of sugars and acids as mass %?	This is calculated on the basis of %DM only (bioliquid DM / feedstock DM). ~(41t/h x 13% DM) / (15t/h x 60% DM) ~59%.
5	But limited market prices. Would better than DKR be possible? Do you envisage problems with coating and smell issues and see possible solutions for it?	The 3D plastics will likely exceed the DKR. We don't envisage problems with coating nor smell and have indications from visitors that they have never seen the like.
5	Are recovery percentages known yet? How critical are the 2D plastics at DKR specs? Included in the business case sensitivities +20/-20%?	The listed figures are expected figures to be confirmed in a test that will take place after the Cure waste trial and further sorting tests. The sensitivity on the total plastic fraction (2D and 3D) are included
6	What is the expected net value range of the gas produced, which is used for the business case?	The figure presented in Appendix 1 is used in the business case.
6	Are additional measures for water removal likely / economic?	This is investigated together with a Dutch expert and might be feasible.

Doc. no. 2200065

Page	Question	Answer
6	What is the typical composition of the brine? What type of disposal is expected? Does it contain (NPK) products to be recovered in future versions?	Yes it contains among others NPK products but also everything else which is not water and a part of the NH3. There is a potential upside in the future that this fraction can be used as fertilizer but we have not accounted for it in the business case.
6	Capture to pure CO2 is nice for greenhouses.	Indeed. It can also be purified to food grade if it is found feasible.
6	Where do batteries end up?	The small household batteries will go with the Bioliquid and are taken out within the preparation step of the Bioliquid. It will be a mix of batteries and smaller metal parts.
6	No danger of metals concentration in recycle i.e. from damaged batteries?	As it is a mild treatment of the waste and that the batteries are removed prior to any "pressing" of fractions, it is not foreseen to be a danger.

Page	Question	Answer
7	No values present of other settings? This gives a process window showing the process sensitivity for variations in the settings and conditions.	This is the setting which will be used and it will not change unless an ongoing trend is seen in the results of the enzyme treatment. These settings are based on our experiences in the many campaigns we have done and will be reflected in the design of the equipment, off course with margins to be able to change if we see a necessity in the future.
