YRKESHÖGSKOLAN NOVIA

Final report 2025

Power of potatoes

Nick Verherstraeten

Gijs Harbers

Lisa Calvin

Tuur Lowie Ons

Maarten Decoster

EPS

Spring Semester 2025

Novia UAS

YRKESHÖGSKOLAN NOVIA

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ABBREVIATION	FULL FORM
POP	Power of Potato
WP	Work Package
PPW	Potato peel waste
PPW-FR	Potato peel waste fermentation residue
EPS	European Project Semester
MS	Microsoft
WBS	Work Breakdown Structure
CAPEX	Capital Expenditures
OPEX	Operational Expenditures
LCA	Life Cycle Assessment
SHF	Separate Hydrolysis and Fermentation
SSF	Simultaneous Saccharification and Fermentation
CO_2	Carbon Dioxide
CH_4	Methane
H_2	Hydrogen
CO	Carbon Monoxide
VOC	Volatile Organic Compounds
H_2S	Hydrogen Sulfide
NM^3	Normal Cubic Meter
FAME	Fatty Acid Methyl Ester
B100	100% Biodiesel (pure biodiesel)
GFN	Green Fuel Nordic
REG	Renewable Energy Group
PSA	Pressure Swing Adsorption
TRL	Technology readiness level
NGO	Non-Governmental Organization (inferred if used)
CHP	Combined heat and power

1 Introduction

1.1 Introduction project

The climate crisis is one of the most significant challenges humanity faces in our generation. Excessive energy consumption and overproduction play a large role in the rise of energy and product demand and thus an overreliance on fossil fuels. To combat this, multiple eco-friendly solutions have been set in place over a wide variety of sectors that each have their own influence on the climate crisis.

This project focusses on the food production sector, and more specifically the potato industry. In the potato industry, millions of kilograms of waste are produced every year (approximately 21,600,000 kg) in the Ostrobothnia region of Finland.

For every kilogram of potato waste produced, resources like clean water and energy are needed, which ultimately go to waste. To put this waste to better use, new methods of recycling potato waste must be pioneered and implemented.

The project, "The Power of Potato," explores the potential of utilizing surplus potato waste as a resource for biofuel production. Divided into multiple subprojects called work packages (WP). By addressing both environmental and economic concerns, the project aims to contribute to the growing field of renewable solutions.

This document outlines the project's purpose, key stakeholders, objectives, and potential challenges while outlining its scope and limitations to establish a clear direction for its development.

Figure 1. Potato field

1.2 Introduction team members

The project is worked on by five team members, all having their own countries, backgrounds and degrees.

1.2.1 Nick Verherstraeten

Figure 2. Nick Verherstraeten

I am from Belgium and currently studying Energy Technology with a focus on sustainability and climate at Thomas More in Geel. I am 27 years old and in the final year of my bachelor's degree.

I chose to pursue an international internship to broaden my horizons and immerse myself in new cultures. I specifically chose the EPS program because its projects focus on sustainability, a cause that is close to my heart. Additionally, I wanted to gain more hands-on experience in this field.

My role will be that of a project coordinator. I chose this position because I want to take on a leadership role, as I have limited experience in team management and project coordination. Through this opportunity, I hope to develop my leadership skills and grow in this area.

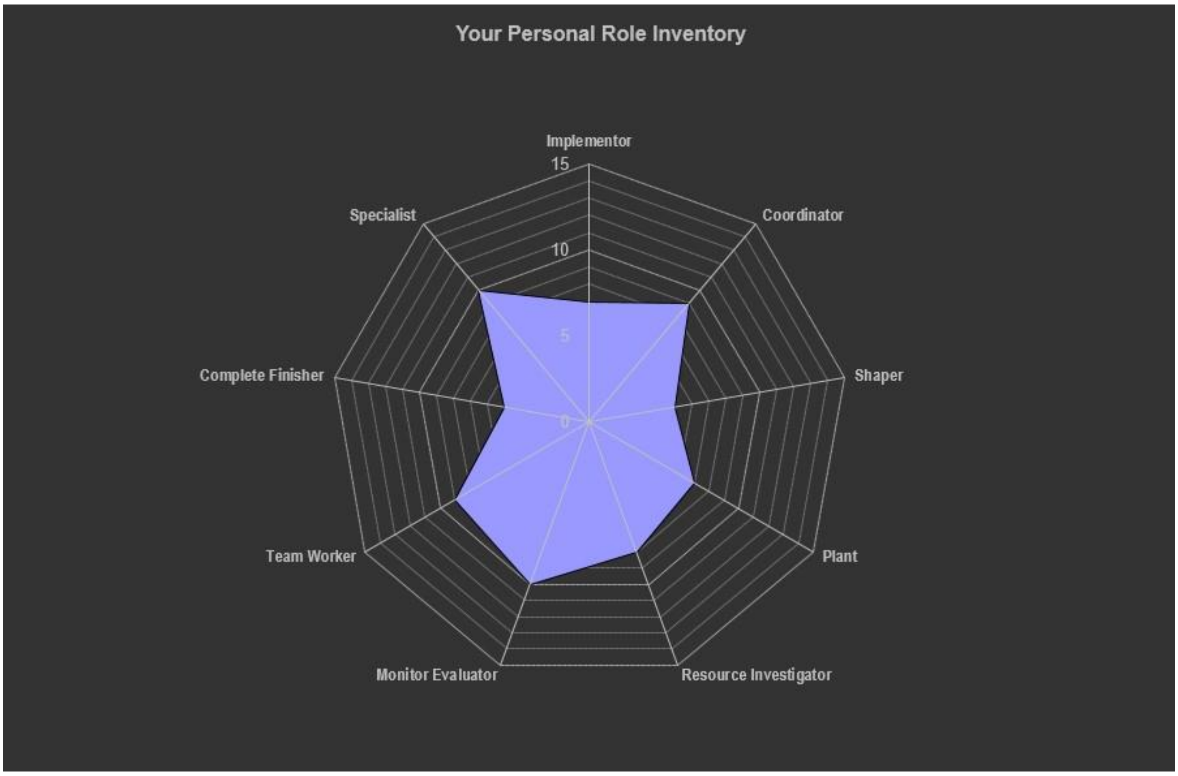

Figure 3. Outcome Belbin test Nick Verherstraeten.

Overall, this Belbin test shows a balanced profile, I will focus on the strengths of my lowest scores and the weaknesses of my highest scores.

I scored a noticeably lower score in Complete Finisher and Shaper. Shaper is said to provide the necessary drive to keep the team focused on the task at hand. This is a point I need to work on, as I have previously found it challenging to stay on track.

As the project coordinator it will be my task to ensure that this is the case. Complete Finishers like to work on the finishing tasks they enjoy polishing the work and search for the last couple of errors in the project. I have in the past been satisfied with work a bit prematurely leaving in some mistakes that would have been easy to get rid of. I could improve in this field by planning more time and making the effort to take a second and third look.

My strongest scores are in the fields of Monitor Evaluator and Specialist. Monitor Evaluators can lack drive and the ability to inspire the team while being overly critical. As the project coordinator this is a pain point as I will have to find a way to overcome this shortcoming. A specialist risks focusing too much on a specific part of the project and can get hamstrung on technicalities. I would say that sometimes I put a lot of importance on small things, but I believe that I have learned to let go of them if the team does not share that belief.

Overall I agree with these results I recognize the different strengths and allowable weaknesses from previous experiences. I believe it is also good exercise to pinpoint your personal working points.

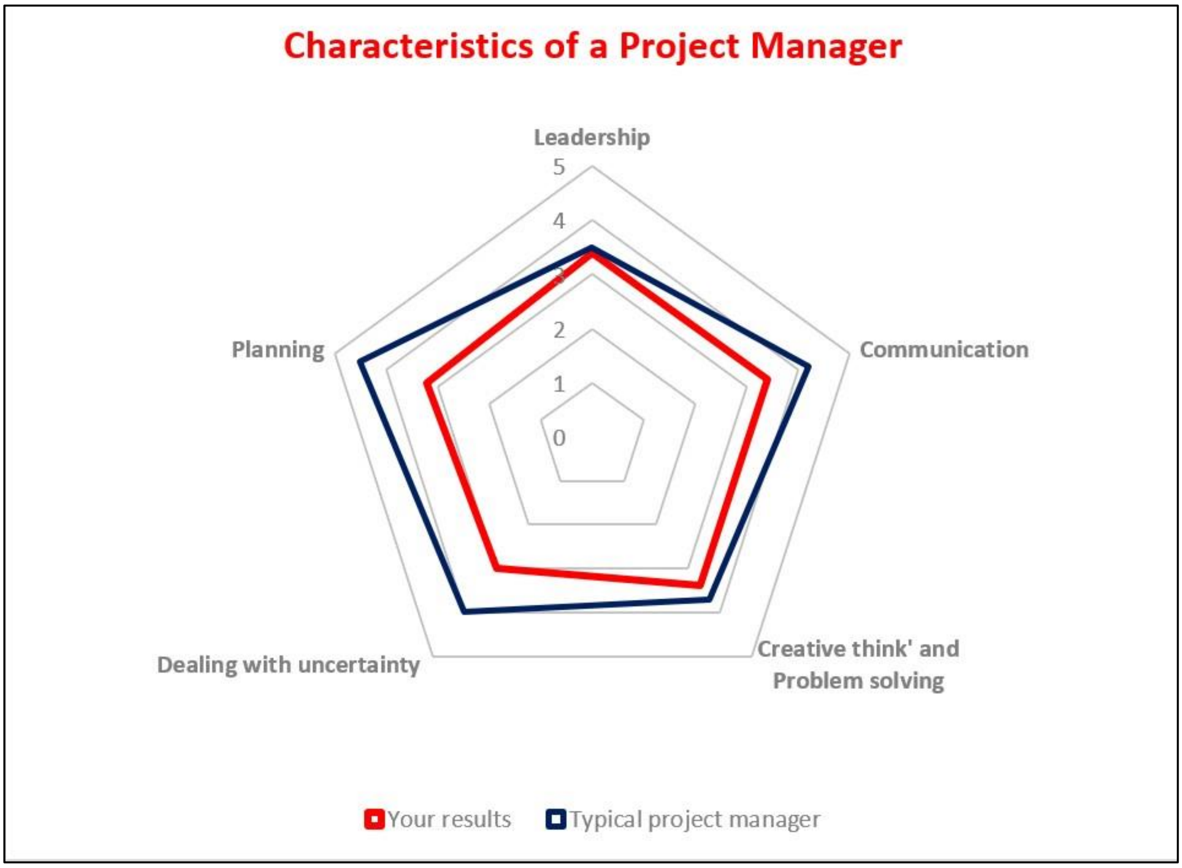

Figure 4. Outcome leadership test Nick Verherstraeten.

This test shows that as a project manager I still have some fields to improve in. Communication is an essential aspect of any team undertaking. It appears that I will need some more practice to convey information clearly and effectively.

Dealing with uncertainty can be seen as adaptability or flexibility. Where I lack in this department is making confident choices despite having uncertainty.

For planning as this is my first time being a project coordinator, I have little experience in things such as time management or goal setting. This can make the project feel a little chaotic at times.

1.2.2 Gijs Harbers

Figure 5. Gijs Harbers

Ì am from the Netherlands, where I study applied physics at Saxion university of applied sciences in Enschede. I am 20 years old now and I have been studying physics since I finished high school at the age of 16. Right now, I am in my 3rd to last semester to finish the bachelor’s degree, meaning after the EPS project, I have one full school year left for my degree.

Physics stood out to me in high school since I was always intrigued by the ways everything worked. Because of this I chose applied physics as my bachelor’s study, since it prepares me to apply my knowledge of physics in the jobs I will be taking later in my life.
For this, learning how to work professionally and in groups is an important factor. Therefore, I chose to participate in the European project semester, which brought me to this project. My primary skills are my knowledge in fields such as physics, automation and project management. I am also well-acquainted with writing reports. This will be beneficial for the project.

For the project I will act as secretary, which doesn’t involve anything out of the ordinary except for taking the necessary notes in meetings. I will also function as a regular team member, participating in a wider variety of tasks.

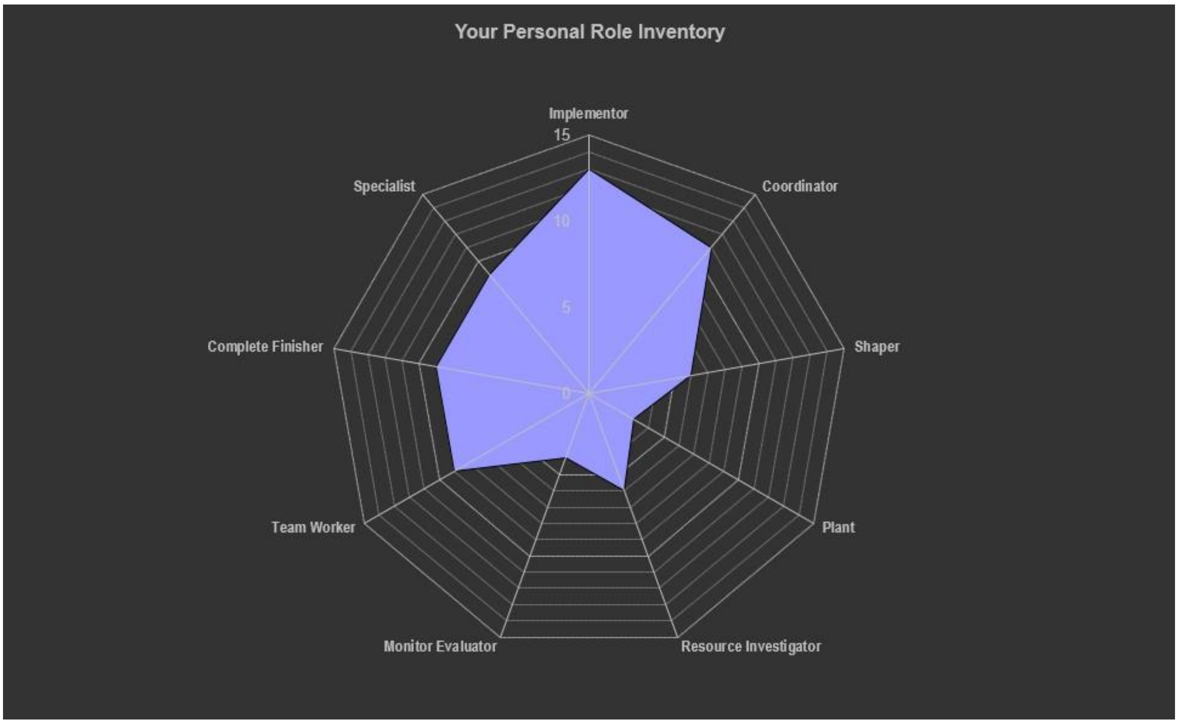

Figure 6. Belbin test outcome Gijs Harbers.

It is noticeable from the outcome of my Belbin test that I am generally good in the qualities on the top and left side of the compass shown in Figure 6. Some qualities that jump out that are not in my field of expertise are monitor evaluator and plant. A person with a high score on the quality plant is said to have highly creative solutions in unconventional ways. This is indeed not one of my qualities as I tend to stick to the usual solution or the one that is the most orthodox. I also agree with the outcome of the test that states that I am not that much of a monitor evaluator. A person with a high score in monitor evaluator is said to be very listening to other teammates. Now I do this, but not in the extent the monitor evaluator does this. A monitor evaluator is often described to have a weakness in the sense that they can lack the drive to inspire others and be too critical.

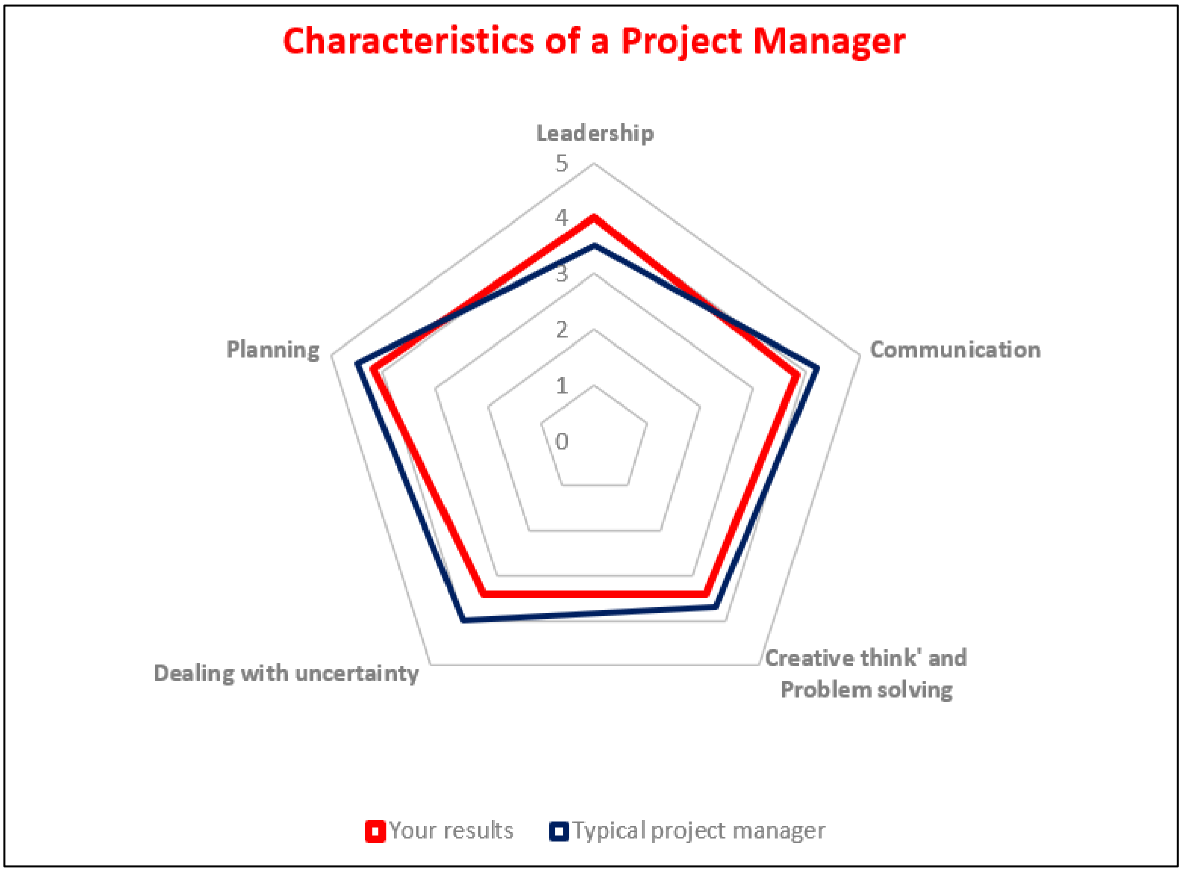

Figure 7. Leadership test outcome Gijs Harbers.

I can conclude from the outcome of the leadership test, that I am not the best person to be leader of the group. Except for the factor leadership, I fall short on every project manager quality compared to the typical project manager. Now I do agree with this test as I do like to inspire my fellow group members to work on the project, but I never specifically learned the rest of the skills that come with the trait of being a project manager.

1.2.3 Lisa Calvin

Figure 8. Lisa Calvin

My name is Lisa Calvin, and I come from the south of France, not far from Montpellier.

I'm a fourth-year student at the ENIT, the school of Mechanical and Industrial engineering of Tarbes. During our course we can do a year and a half of internships as well as a semester of international mobility.

During my studies I was able to acquire a range of skills, such as handling CAD software like Catia, machining and mechanical engineering, but my main specialty is industrial engineering, with the implementation of continuous improvement within companies.

I chose to join the EPS program to have the opportunity to carry out a project in a multicultural group and to discover Finland and its culture.

Finally, as far as our project is concerned, although I don't have a specific role, my responsiveness and commitment will be very welcome.

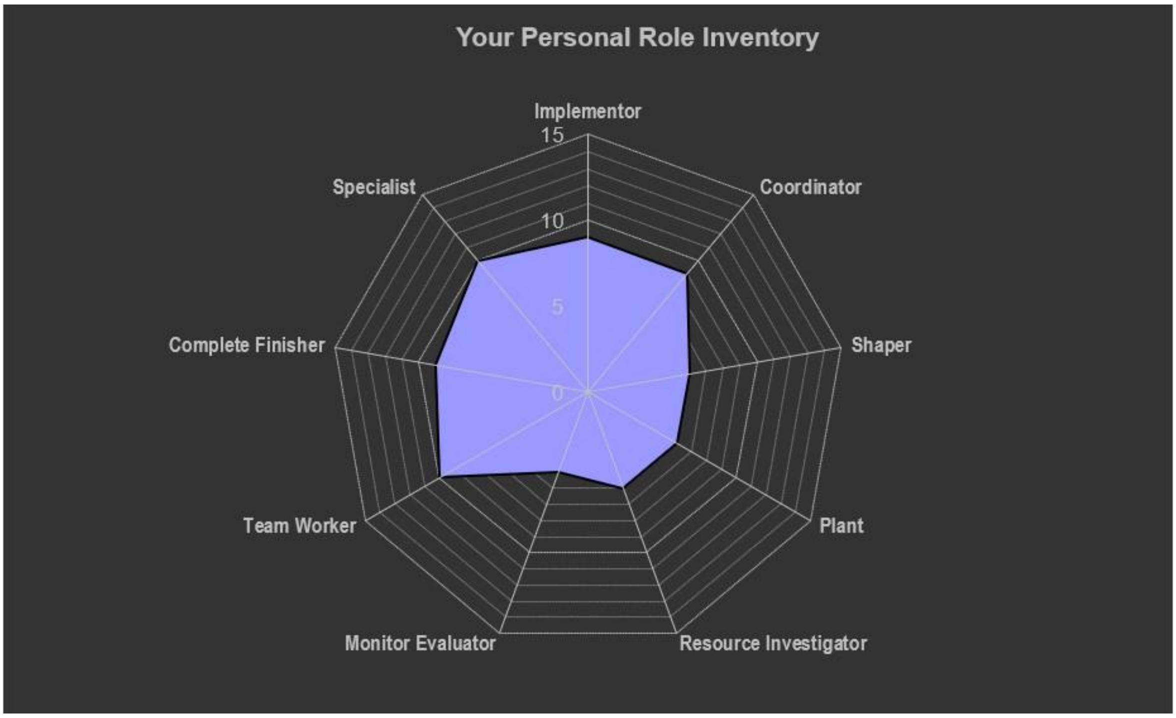

Figure 9. Belbin test outcome Lisa Calvin.

Looking at my Belbin Test, I can clearly see where my strengths lie and where I have room to grow. I score highest in the roles of Implementor, Coordinator, and Specialist. This suggests that I am reliable when it comes to turning ideas into actions and making sure things get done efficiently. From what this test says, I am organized, disciplined, and tend to approach work systematically. As a Coordinator, I have a natural ability to delegate effectively and bring people together toward common goals. Being a Specialist also shows that I have deeper knowledge in certain areas, and I'm able to apply that expertise to add value to the team.

However, there are areas where I'm less naturally inclined. My lower scores as a Resource Investigator, Monitor Evaluator, and Plant suggest potential pitfalls. I may not always be the best at seeking out new opportunities or thinking outside the box for creative solutions. Sometimes, I might miss exploring alternative views, and I may need to make a conscious effort to remain open-minded and challenge assumptions. Additionally, I could benefit from developing my evaluating skills and objective analysis when making decisions.

In summary, I excel at bringing structure and expertise to projects, coordinating team efforts, and delivering reliable outcomes. But I need to be mindful of staying open to new ideas and ensuring I don't overlook creative solutions.

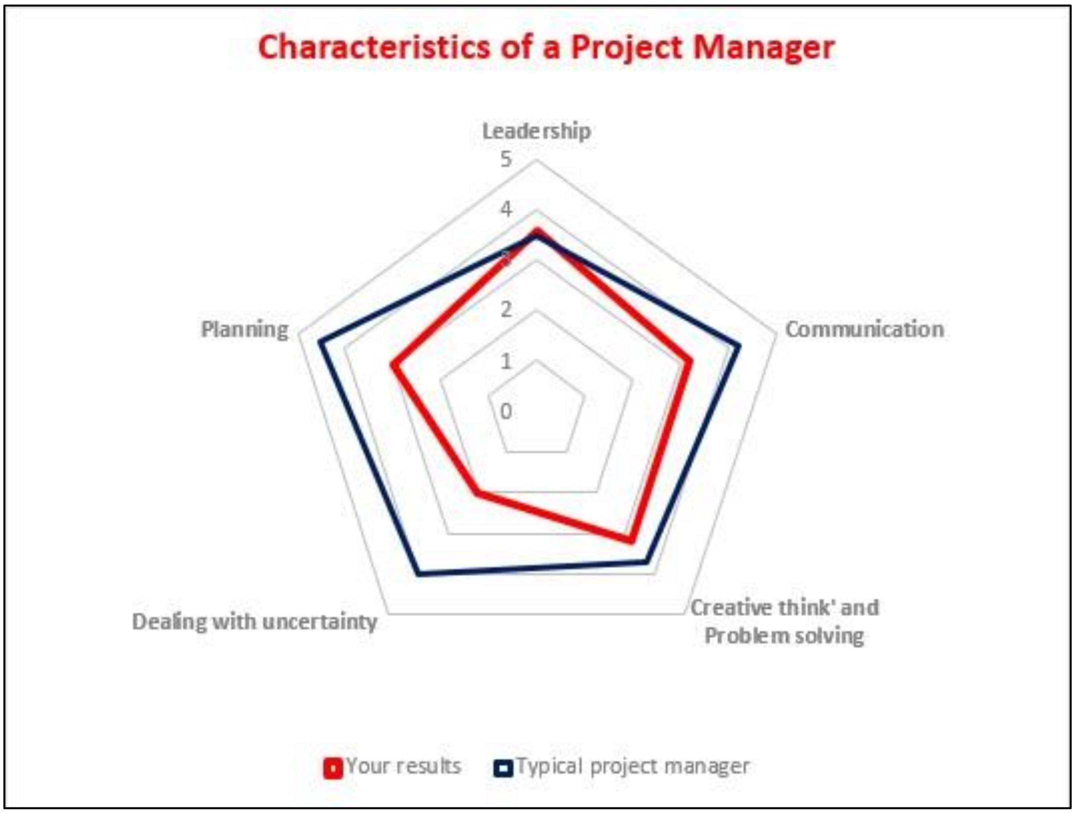

Figure 10. Leadership outcome Lisa Calvin.

According to my results, I have strong leadership and communication skills, which means I'm effective at guiding teams and keeping everyone aligned. I also do well in creative thinking and problem-solving, showing I can come up with solutions when challenges arise. However, I score lower in planning and dealing with uncertainty. This suggests I might need to focus more on structured planning and becoming more comfortable navigating unpredictable situations.

1.2.4 Tuur Lowie Ons

Figure 11. Tuur Lowie Ons

I am Tuur Lowie Ons, an enthusiastic energy management student from Belgium.
To be more specific from Antwerp, where I also study. I study at AP university because of its good connotation for the technical/energetical courses. At this university I have broadened my knowledge and my interests. Mainly containing everything that has to do with green energy, renewables and the electrification. Because of these interest my plan is to go as far as I can in this path of energetic thinking, beginning with doing my masters in renewable energy.

Because of my active studies I think I can bring the green thinking into our project. I also got a little background in project management and a lot of group projects. In those projects I have been the group leader, therefore I would call my leadership skills quiet good. I hope to learn a lot from this experience such as improving my English and broadening my soft skills.

All in all I think I can be an useful asset in this project where the sustainable green - thinking stands central. I will participate as a regular team member. This means being involved in a wider variety of tasks.

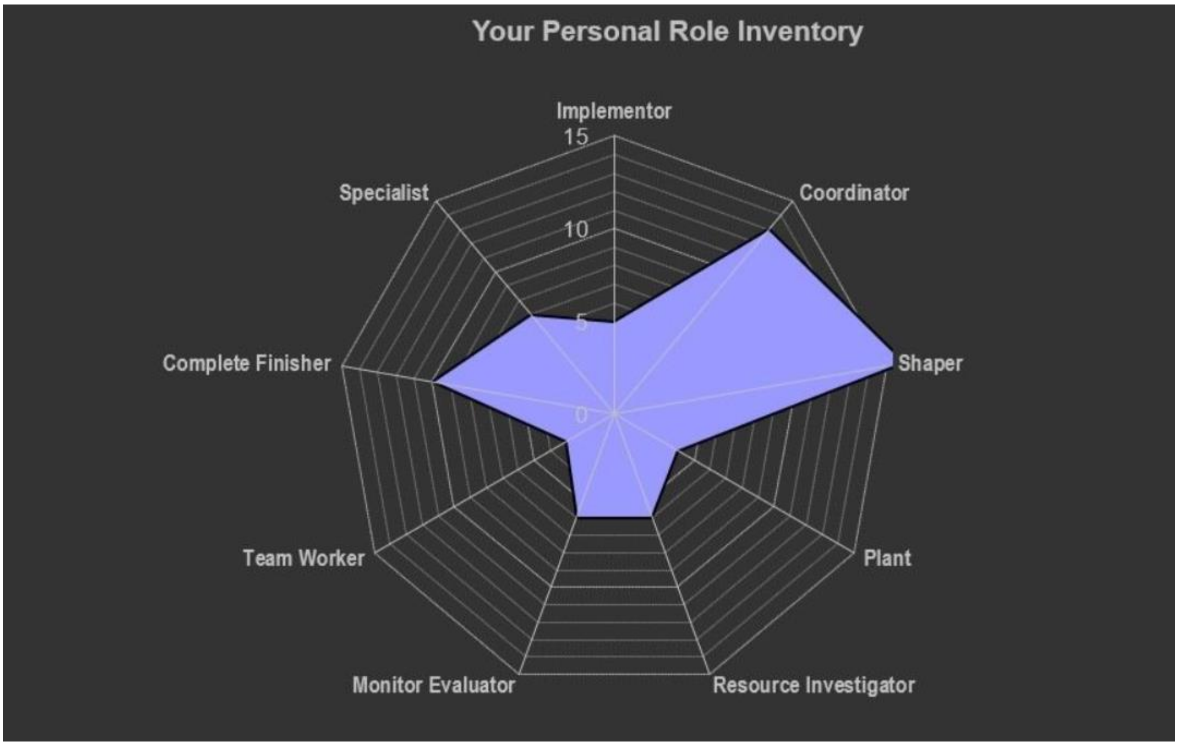

Figure 12. Belbin test outcome Tuur Lowie Ons.

I would say this picture describes my personality as a leader quite well. I do have a history of leading projects at my home university. Which gave me the chance to come in contact with many of the aspects from the test. I definitely agree with the shaper/coordinator position, as I see those as my strengths. I also have to agree with the fact that sometimes, I am not the best team worker. However, I think a leader sometimes should be harsh/demanding and not the best team worker to get to the set goal. The reason I feel that way is because I have experienced it multiple times.

As u can see my pitfalls focus mainly on the creative side. I totally agree with this, and because of this. A project of mine often falls into a tunnel vision for me. This because I don't always look for a new way, or say a creative way. And once I found a way I will try my best to make this happen. And that is also what this test has shown by the term complete finisher.

All in all, I mainly agree with what the test has shown us. The mediocre score each, show a well representable score according to me. As do the extreme scores, although I hope I can better my low scores. And even work on my high score, as they do not necessarily indicate it's a positive score.

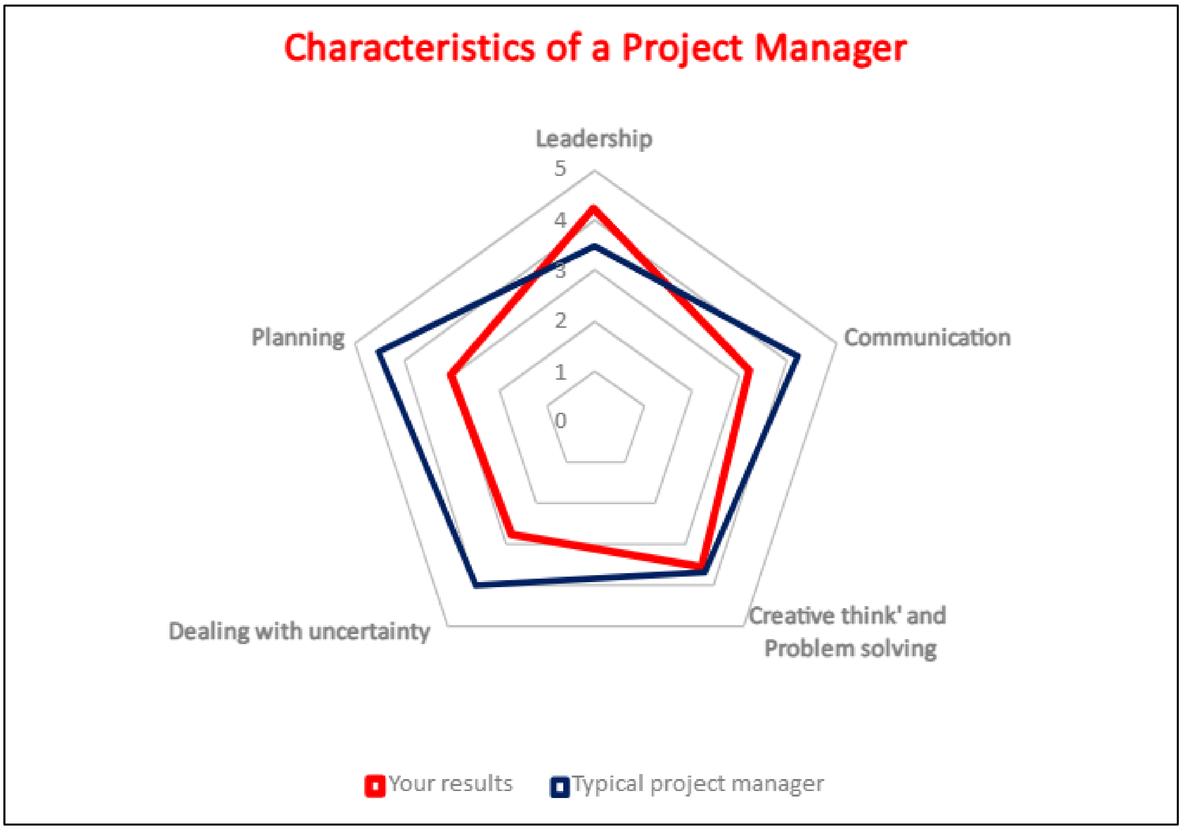

Figure 13. Outcome leadership test Tuur Lowie Ons.

After taking the leadership test, I found some results to be accurate, while others did not fully align with how I see myself. One result I strongly disagree with is my lower leadership score. From my experience leading projects at my home university, I know that I am comfortable taking charge, setting goals, and guiding a team toward success. This also aligns with my Belbin test results, where I identified with the Shaper and Coordinator roles. Both of which emphasize strong leadership. While I recognize that I can sometimes be direct or demanding, I see this as an essential trait for achieving goals, not as a weakness in leadership.

On the other hand, I scored relatively well in creative thinking and problem-solving, which I don't entirely agree with. I know that I tend to develop tunnel vision when working on a project, focusing on execution rather than exploring new and innovative approaches. This aligns with the Belbin test I took.

Other aspects of the test, such as my scores in communication, planning, and dealing with uncertainty, seem more balanced. While I do believe I am structured and goal-oriented, I can see how my planning and adaptability could be areas for improvement. However, I recognize that flexibility/adaptability is important in leadership, and I am open to developing this skill further.

Overall, while I appreciate the insights from the test, I do not fully agree with all the results. I believe my leadership skills are stronger than indicated, while my creativity score may be overestimated.

1.2.5 Maarten Decoster

Figure 14. Maarten Decoster

My name is Maarten Decoster and I am 21 years old. I come from Belgium from a small village next to Brussels.

I study at the AP university in Antwerp where I will be finishing my professional bachelor in energy management. When you enter your last year of a professional bachelor's degree you either do an internship or go on Erasmus which was an easy choice for me.

Due to my studies, I have lots of experience in energy-related calculations and working with big formulas in MS Excel. My study is about sustainability, green energy and smart management systems.

The reason I wanted to join the EPS program was primarily to improve my skills in collaborating with a team. Secondary I wanted to get to know the Finnish culture and experience it.

In this project there is not a specific role that I got assigned to which is why I will help on the project sustainability side and if necessary, I can use my skills in Excel to help there.

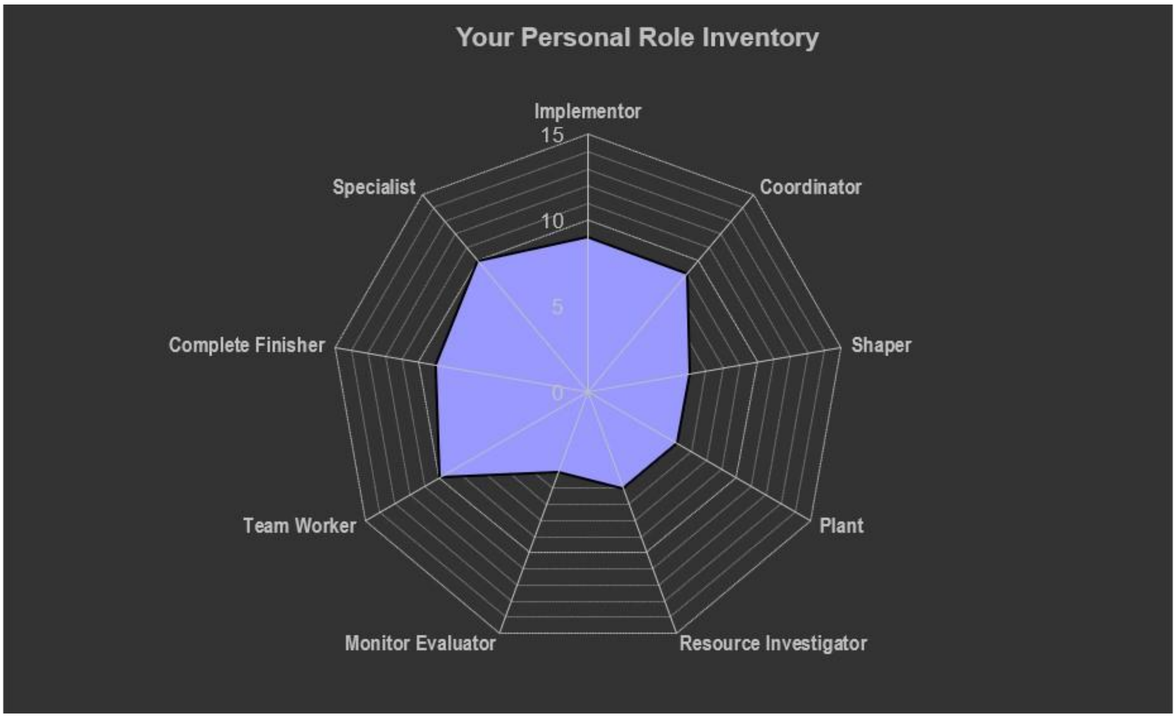

Figure 15. Outcome Belbin test Maarten Decoster.

By looking at the outcome of the Belbin Test, I don't really have one specific quality that really jumps out of there. My two highest scores are for "Team Worker" and "Specialist". I feel that these score are not 100 percent accurate but they are not completely wrong either. A "Specialist" has the properties that he likes to do the things where he is specialized in and everything else seems a little useless to him. I can definitely see myself in this role. When there is a problem that has something to do with economics instead of sustainability, I lose my interest very quick. I think the "Team Worker" role also fits me pretty good. I like to solve problems together and use everyone's idea's to get to a good solution.

Some things that are important to notice are the pitfalls of these roles. For a "Specialist" this is getting to deep into the details about the part where they are specialized in. When a project focuses on a subject outside a specialist's area of expertise, they can easily go of scope when they find something that interest them.

For a "Team Worker" the usual pitfalls are avoiding confrontations and creating a team environment where the serious issues aren't addressed sufficiently.

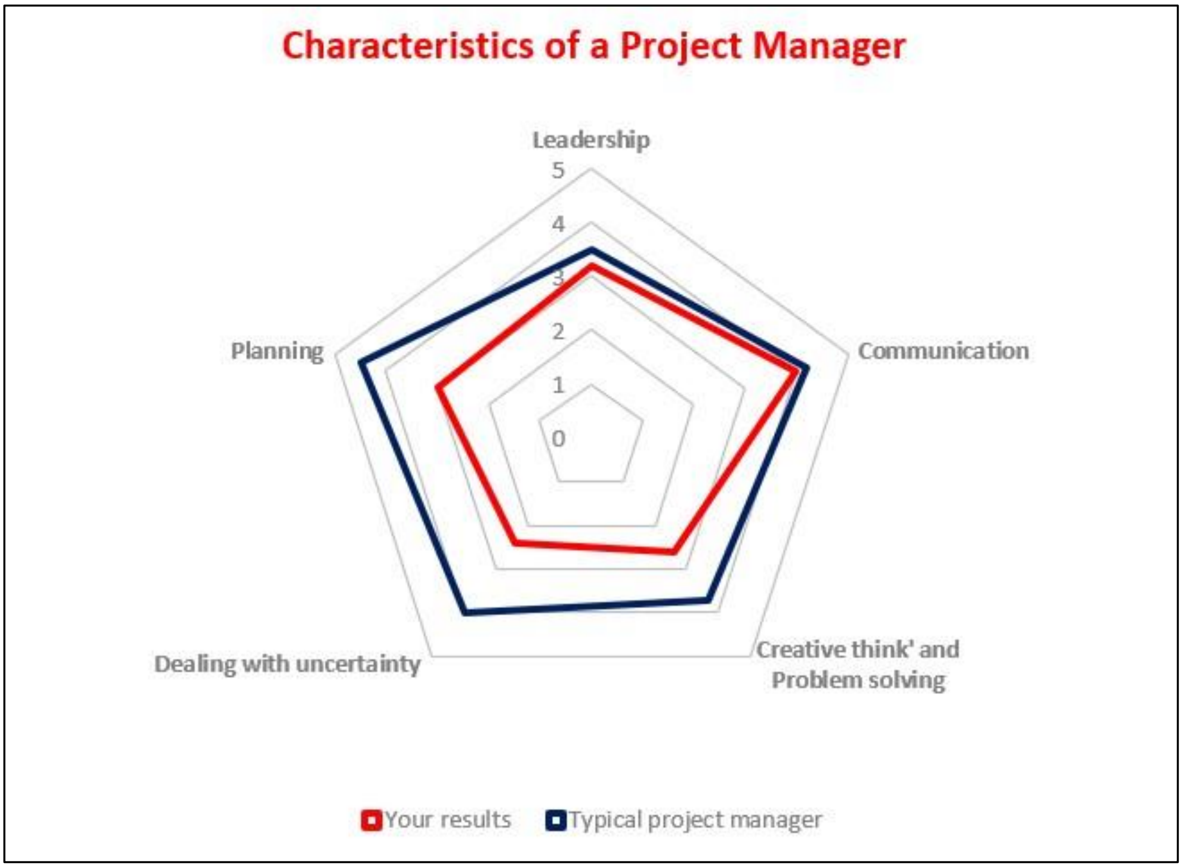

Figure 16. Outcome leadership test Maarten Decoster.

From what I can tell from the test I wouldn't be a very good leader. Only the communication and maybe the leadership part are pretty good for me. Planning is totally not my strong point and dealing with uncertainty isn't either. I can conclude with this test that I need a lot of improvement one many of these topics to become a leader/project manager.

2 Problems definition & objective

2.1 Problem definition

Ostrobothnia produces a large amount of potato waste that is not fully utilized. The end of potato exports to Russia and rising energy costs makes this issue more pressing. Finland is also moving away from peat-based energy, creating a need for new renewable fuel sources.
The challenge is to find a sustainable and cost-effective way to convert potato waste into E-fuel. The solution must be technically feasible, economically viable, and environmentally friendly.
Our project centers around work package 2 (WP2). Which aims to probe the different ways potato waste can be converted into biofuels.

2.2 Objectives

- Identifying available technologies and evaluating their feasibility for the project. This includes examining the production methods of biogas, bioethanol, methanol and synthetic diesel in the region to determine which solutions can be effectively adapted to our needs.
- Assessing regional infrastructure, energy sources and feedstock availability to select the most suitable approach. The goal is to align the best technology with local conditions for optimal efficiency.
- Studying successful biofuel and synthetic fuel projects worldwide to identify key success factors and best practices. This will allow us to apply proven strategies and adapt them to our regional context for sustainable and effective implementation.

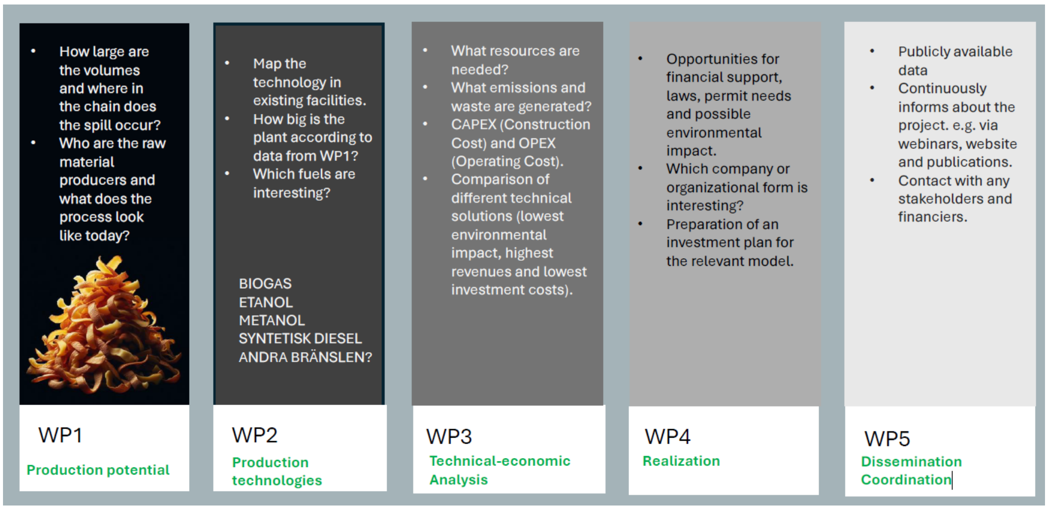

Figure 17. The 5 Work Packages.

3 Methodology

The purpose of this methodology is to provide a clear overview of how the Power of Potatoes project was developed. Together the methods used to achieve its objectives.
The European Project Semester (EPS) began on February 5, 2025, and will conclude on May 20, 2025, with a midterm presentation on March 25, 2025, and a final presentation on May 20, 2025.
For communication, the team used MS Teams and WhatsApp for internal discussions, while MS Teams and Outlook were used for external communication, including interactions with the project manager.
Our team held weekly meetings, primarily in person but occasionally online. Each meeting was documented in a report that included:

- The start time
- A review of the previous week's action points
- Current action points
- Upcoming tasks, assigned responsibilities, and deadlines
- Open questions for discussion
- Scheduling of the next meeting
- The end time of the meeting

At the start of the project, various tools were used to help team members get to know each other and assess competencies. These included:

- Project Model Canvas: A large paper canvas where we outline our strengths, weaknesses, personal goals, project roles, stakeholders, and deliverables.
- Belbin Test: Analyzed and compared among team members to understand team composition.
- General Leadership Test: Provided insight into individual leadership styles.
- Hofstede Country Comparison Tool: Used to identify potential cultural differences within the team.
- Team Charter & Stakeholder Register: Developed to define team expectations and involved stakeholders.

To anticipate potential challenges, a risk assessment was conducted to identify possible pitfalls.
To ensure the project stayed on track, a Work Breakdown Structure (WBS) and a detailed schedule were created.

4 Project delimitations

It is important for a project this size, to have a clear scope. Our goals are based on Figure 17. The 5 Work Packages. Our group's focus sits in Work Package 2 (WP2). The goals and scopes associated with subsequent phases (WP3, WP4, WP5, and WP6) are outside the delimitations of this specific project.

Thus, we are focused on the technologies themselves, and the biofuels that are output from the processes. Another task is focusing on the scaling of the project. So, we can roughly estimate the size which is needed to process the waste.

Our scope does not contain the framing of the resources nor the financial aspect. For the sake of the final comparison, it was decided to include a cost analysis as a criterion. This means we won’t think about any investments which are to be made. Stakeholder management will not be any of our concerns either. Because our job is purely the theoretical aspect of the project. The practical aspect aligns more with the work packages of the subsequent groups.

We hope this gives a clear view of the scope of the project and more importantly what lies outside the scope.

5 Planning

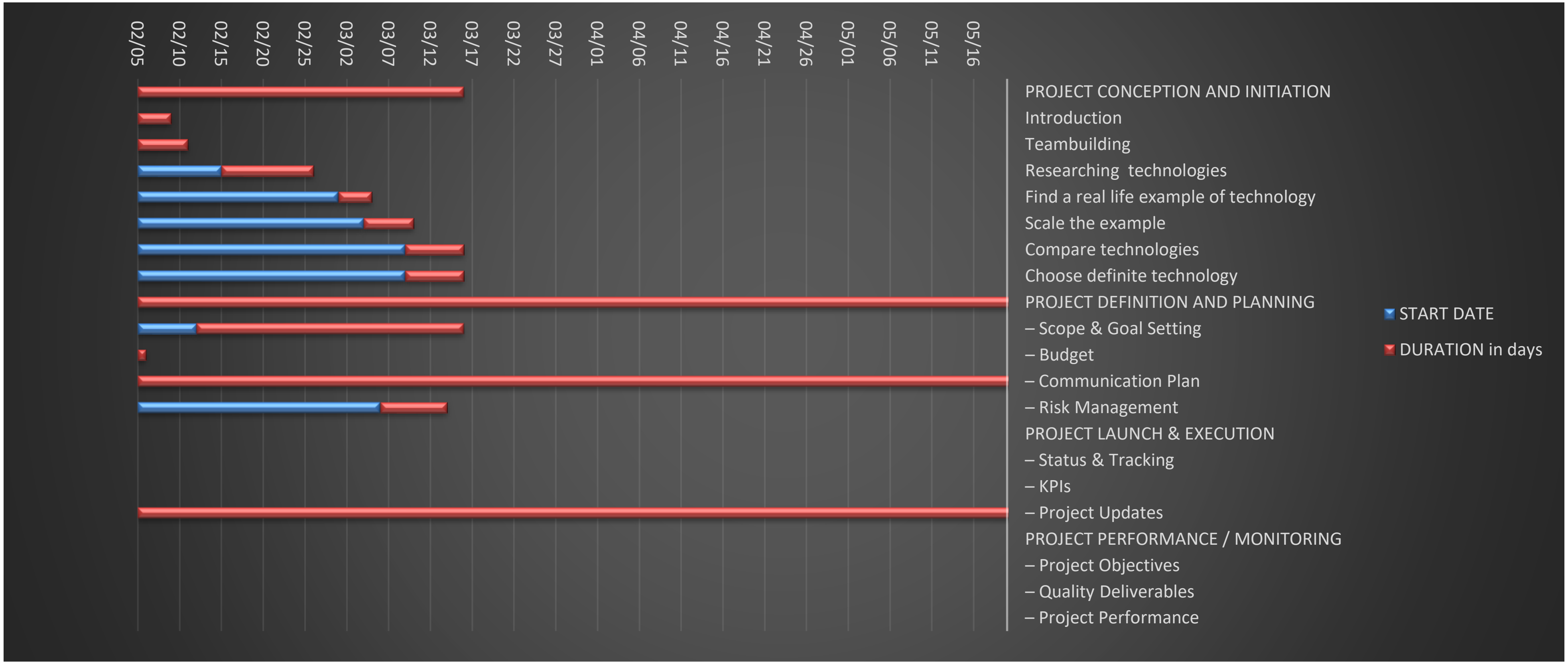

Figure 18. Chart planning of the planning.

WBS NO.	TASK NAME	STATUS	ASSIGNED TO	START DATE	END DATE	DURATION in days	COMMENTS
1,3	Researching technologies	Complete		02/15	02/25	11	Get to know all possible technologies
1,4	Find a real life example of technology	Complete		03/01	03/04	4	
1,5	Scale the example	Complete		03/04	03/09	6	Ge to know the "factory" how do they apply the technology, how much do they produce
1,6	Compare technologies	In Progress		03/09	03/15	7	
1,7	Choose definite technology	In Progress		03/09	03/15	7	Choose the most feasable technology, look at different aspects. Economical, ecological and environment
2	**PROJECT DEFINITION AND PLANNING**	**In Progress**		**02/05**	**05/20**	**105**	
2,1	– Scope & Goal Setting	In Progress		02/12	03/15	32	Scope decided, goals not yet
2,2	– Budget	Complete		02/05	02/05	1	Already decided in earlier stages
2,3	– Communication Plan	In Progress		02/05	05/20	105	Weekly meetings without guide, daily updates after class
2,4	– Risk Management	In Progress		03/06	03/13	8	
3	**PROJECT LAUNCH & EXECUTION**	**Complete**				**1**	
3,1	– Status & Tracking	Not Started				1	Not decided yet
3,2	– KPIs	Not Started				1	Not decided yet
3,3	– Project Updates	In Progress		02/05	05/20	105	Weekly meetings with our project guide
4	**PROJECT PERFORMANCE / MONITORING**	**In Progress**				**1**	
4,1	– Project Objectives	In Progress				1	
4,2	– Quality Deliverables	On Hold				1	
4,4	– Project Performance	Not Started				1	

Figure 19. Planning of the project.

6 Risk analysis

To execute a risk analysis, a risk assessment form is set up (Sienkiewicz, 2022). In this table the first column is used to describe the possible risks, the second column is used to describe the likelihood and the third the impact. The likelihood and the impact of the risk are both scaled on a 1 to 5 rating system, where 1 is lowest value, and 5 the highest. In the fourth column, the risk-rating is calculated, this is the likelihood value and impact multiplied with each other. The risk-rating is therefore a rating from 1 to 25.

- 1–6 (low): low-rating risk are not very likely to happen, and if they do, they will not be a threat to the project.
- 7-12 (medium): medium-rating risk might happen at some point. The risks are not a significant risk to the project but should not be ignored.
- 13-25 (high): High-rating risks are likely to happen. The consequences are very significant and can cause the project to fail.

The last column is the response column. In here, the appropriate action is noted according to risk-rating of the selected risk.

Table 1. Risk assessment form for the project.

Risk	Response	Owner of the risk	Likelihood	Impact	Risk-rating
Prioritizing free time over tasks	Having a according planning to prevent free time interfering with work.	Nick	4	3	12
Not properly defining tasks	Defining the tasks on paper in the notes.	Gijs	3	5	15
Going too much into detail	Clearly define the tasks.	Gijs	3	1	3
Missing deadlines	Keeping up to date with the planning and attempting to finish tasks ahead of the planning.	Everyone	3	5	15

Having communication issues.	**Mind culture-communication differences and using notifications.**	Everyone	1	4	4
Having lack of teamwork	**Where needed divide tasks where no teamwork is not possible.**	Tuur	2	3	6
Fallout of a team member	**Communicate about motivation and individual mental states.**	Everyone	1	5	5
Having a lack of knowledge of biofuel	**Read in about biofuels, and communicate with the project manager.**	Everyone	4	4	16
Diverging from the scope of the original project	**Communicate with the project manager regularly about the scope of the project.**	Everyone	4	3	12
Using unreliable sources for the literature research	**Fact check the sources.**	Lisa	1	5	5

7 Belbin Test

The Belbin test is based on nine profiles that each describe a role within a team with specific characteristics and strengths. It also talks about the role's allowable weaknesses.

The nine Belbin Team Roles are: Resource Investigator, Teamworker and Co-Ordinator (the Social roles); Plant, Monitor Evaluator and Specialist (the Thinking roles), and Shaper, Implementer and Completer Finisher (the Action or Task roles). [1]

At the start of the project each team member took the Belbin test to evaluate their perceived score for each team role. In the introduction of the team the individual results will be discussed. [2]

This was done to get an overview of the possible strengths and allowable weaknesses within the team.

Figure 20. Belbin test roles. [1]

7.1 Belbin Test Team

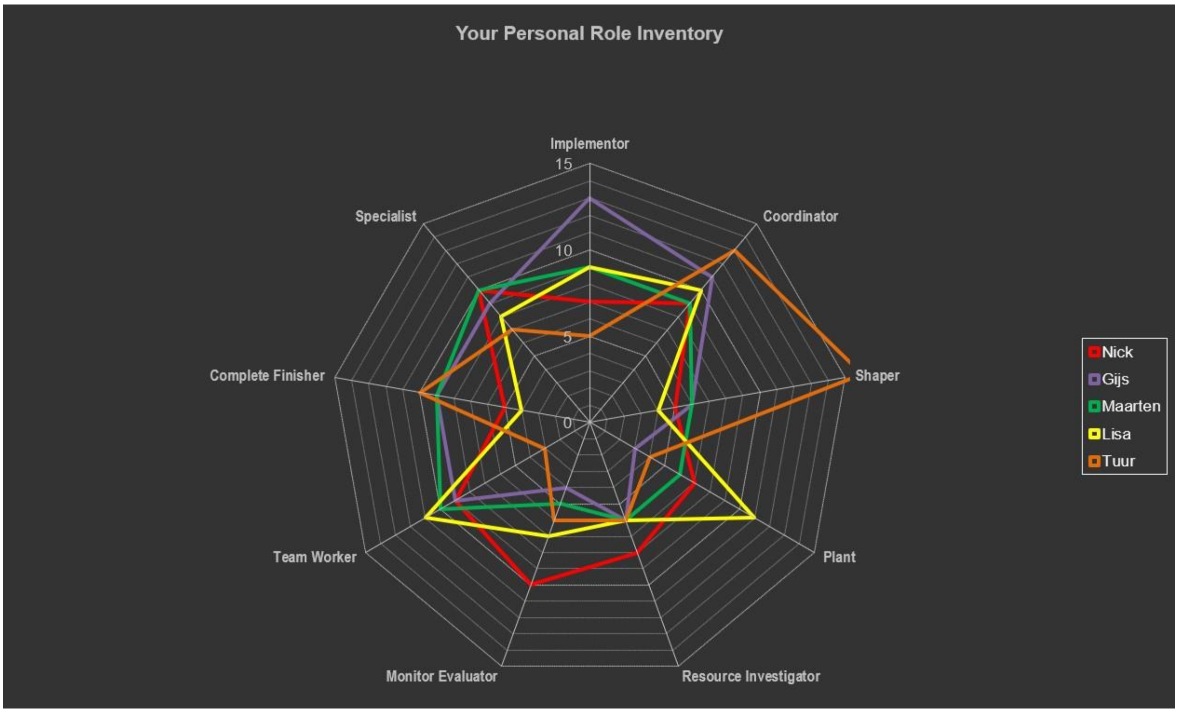

Figure 21. Overlay of all the outcomes of the Belbin test.

We can see in the figure above that we have a few people that are average at almost every role and then we have Tuur that really exceeds as a Coordinator. With this graph we can see that everyone will be a good Team Worker except for Tuur. Lisa exceeds mainly in the Plant role which is a good thing that we have one person in our team who will take on this role. Our Implementor for this project will be Gijs. Maarten and Nick will contribute a little bit in every role.

8 Hofstede cultural dimensions

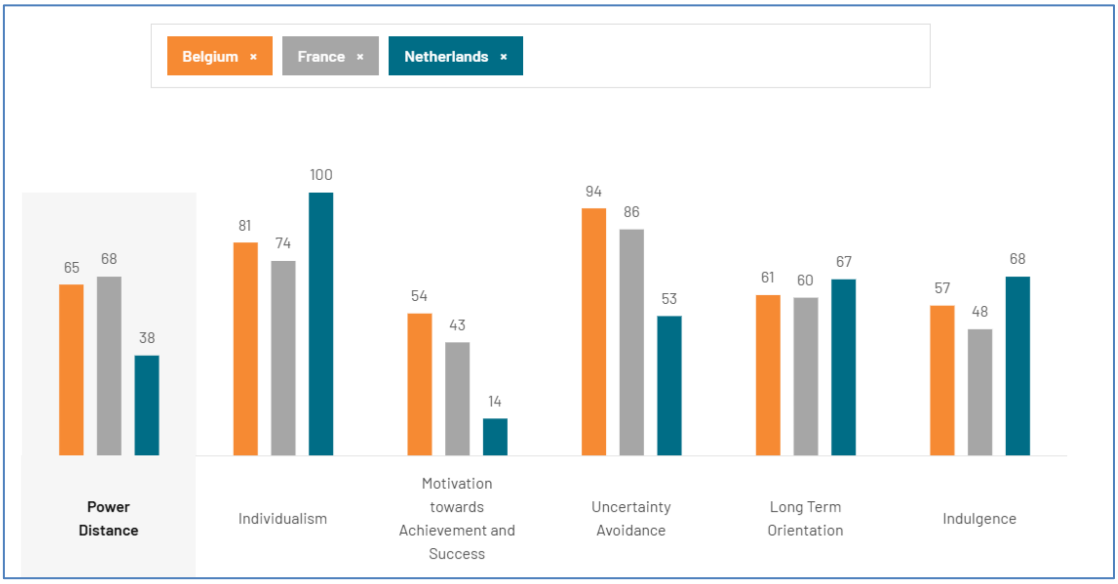

Figure 22. Visual of the country cultural dimensions values.

- **Power Distance**

Reflects a society's attitude toward hierarchy and inequality, measuring how much less powerful members of institutions and organizations accept unequal power distribution.

- **Individualism**

  Measures a society's interdependence, defining self-image as "I" (Individualist) or "We" (Collectivist). Individualists prioritize personal and family needs, while Collectivists rely on in-groups for support in exchange for loyalty.

- **Motivation towards achievement and success**

They focus on achievement, competition, and material success versus care, well-being, and cooperation.

- **Uncertainty Avoidance**

How does a society handle the unknown or accepts uncertainty. Cultures with high scores create strict institutions to reduce uncertainty, while those with low scores are more comfortable with unpredictability.

- **Long Term Orientation**

Describes how societies balance tradition and future challenges. Low score societies like to uphold traditional values and are wary of change, while high score societies prefer adaptability, thrift, and modern education to prepare for the future.

- **Indulgence**

  Difference between indulgent cultures, which allow free gratification, and restrained cultures, which enforce strict social norms and self-discipline. (The Culture Factor Group Oy, 2025)

8.1 Nationalities individual

1. **Belgium**
- Power Distance (65)
- Individualism (81)
- Motivation towards achievement and success (54)
- Uncertainty Avoidance (94)
- Long Term Orientation (61)
- Indulgence (57)

Nick

- *Power Distance*

Mostly agree

- *Individualism*

Agree

- *Motivation towards achievement and success*

With 11 governments, seating the European parliament and 3 languages, it is important to find a consensus and decision making is slow.

- *Uncertainty Avoidance*

Belgium holds the record of longest period without a government

- *Long Term Orientation*

Agree

- *Indulgence*

Agree

Tuur Lowie

- *Power Distance – Agree*

Belgium has a complicated government structure, which results in a need for strong legislation and hierarchy. However, I also believe that the power distance is influenced by conservatism, which can lead to more inequality.

- *Individualism – Agree*

Belgians are quite individualistic, and I see myself as an individualist as well. Personal independence is important, and this aligns with my perspective on Belgian culture.

- *Motivation Towards Achievement and Success – Partially Disagree*

I believe this score should be around 50, as motivation in Belgium is highly dependent on the individual. Generally, people strive for success but only up to a point where they reach personal happiness.

- *Uncertainty Avoidance – Agree*

Belgium's complex governmental structure requires extensive legislation, making certainty avoidance a key characteristic of the country. This is one of the most visible traits in Belgian culture.

- *Long-Term Orientation – Partially Disagree*

While Belgium has a long-term focus, I associate long-term orientation with conservatism. As Western Europe is shifting towards more conservative thinking, I believe this score could be lower. A conservative mindset can slow progress and even reinforce inequality.

- *Indulgence – Agree*

  I believe the score makes sense, as Belgians enjoy life but also balance it with responsibilities. However, I would be open to discussing whether this score should be higher.

Maarten

- *Power Distance*

I think the score of 65 in Power Distance reflects reality quite well. In Belgium, I notice that people generally accept hierarchies and formal structures, especially in workplaces. There's a clear respect for authority, and people are used to following rules and procedures. At the same time, it's not an extreme hierarchy—there's still room for discussion and participation, but overall, people are comfortable with someone being leading them.

- *Individualism*

I definitely agree with the high Individualism score. Belgians are very focused on personal responsibility and independence. From my experience, people value their privacy and tend to prioritize their own goals and family life over group interests. I also think that this mindset encourages people in Belgium to work harder.

- *Motivation Towards Achievement and Success*

I find the score of 54 in this dimension to be a good reflection of Belgian culture. There's a healthy balance between striving for success and maintaining a good quality of life. I've seen that people are motivated to achieve their goals and take their careers seriously, but they also know when it's time to relax and enjoy life. Your job isn't always about competing against one and another, which I personally really like.

- *Uncertainty Avoidance*

Belgians like to be prepared, and I can see how the high score of 94 shows how important structure and clear rules are here. I'm someone who appreciates knowing what to expect, and I think most people around me feel the same way..

- *Long-Term Orientation*

I do not completely agree with this score for Long-Term Orientation. People here often think ahead and take a pragmatic approach to problem-solving, but in my opinion this often fails. Sometimes they do road works for over three years and then they realize that they have just made the situation even worse. So in my opinion this score should be a little lower between 45-50.

- *Indulgence*

Lastly, I think the score of 57 in Indulgence makes sense. Belgians do enjoy life—they like good food, travel, and social activities, but there's also a balance. It's not an overly indulgent culture, and people still respect rules and responsibilities.

2. **Netherlands**

- Power Distance (38)
- Individualism (100)
- Motivation towards achievement and success (14)
- Uncertainty Avoidance (53)
- Long Term Orientation (67)
- Indulgence (68)

Gijs

- *Power Distance*

Agree. In the Netherlands, people don't strive so much for higher positions as in other countries, leading to a lesser value viewed to that position.

- *Individualism*

Moderately agree. Whilst it is true that the Dutch like to work for themselves. The maximum score seems too high since the Dutch can work together on a project when push comes to shove.

- *Motivation towards achievement and success*

Agree. In the Dutch is the culture work to live, compared to the live to work culture in countries like the US. This leads for many Dutch people to see work just to help them financially in life. This doesn't mean the Dutch don't like their job, but rather that they don't strife for higher positions if they already like their place in the company they work at.

- *Uncertainty Avoidance*

Agree. The Dutch have a good balance at taking preventive measurements and working in chaos.

- *Long Term Orientation*

Moderately agree. In the Netherlands it is common to have projects well thought out with high accordance for the future. In my opinion, the score for long term orientation could be higher for the Netherlands.

- *Indulgence*

Agree. In the Netherlands people are raised to be moderate and modest, leading to a correct score of 68.

3. France
- Power Distance (68)
- Individualism (74)
- Motivation towards achievement and success (43)
- Uncertainty Avoidance (86)
- Long Term Orientation (60)
- Indulgence (48)

Lisa
- *Power Distance*

Agree, but the French people often contest this hierarchy (strikes, demonstrations).
- *Individualism*

Yes, France is an individualistic society, especially among the middle and upper classes. The family also plays an important role.
- *Motivation towards achievement and success*

Agree, France is focusing on quality of life with social protection and work-personal life balance, which is moving away from a masculine culture.
- *Uncertainty Avoidance*

I completely agree, it's a paradox typical of the country.
- *Long Term Orientation*

I think it should be lower, because there is a strong attachment to traditions and ideologies, which makes it difficult to see certain structures, such as the administration, evolve.
- *Indulgence*

France is indulgent when it comes to its pleasures (gastronomy, etc.) but not when it comes to bureaucracy, where the climate is often serious or even stressful.

8.2 Nationalities Collective

1. Belgium

Our Belgian team members generally agree with each other, we also believe that this is a typical Belgian trait to find common ground.
- *Power Distance (65)*

We disagree and think it should be lower

Among our Belgian team members, we agree that we have strong hierarchical institutions but disagree with the general score an believe it should be a bit lower.
- *Individualism (81)*

We agree with this high score. Belgium is rather individualist.
- *Motivation towards achievement and success (54)*

We agree that it should be around fifty-fifty.
- *Uncertainty Avoidance (94)*

We agree with this significant score. Belgium has 11 governments and thus needs a lot of rules and regulations. We also think this is a beneficial trait for teamwork. We like to look for compromises.
- *Long Term Orientation (61)*

We believe that Belgium leans towards a more traditional viewpoint but think that the score should be somewhat lower.
- *Indulgence (57)*

We think it should be higher.

8.3 Team

Our team consists of members from neighboring countries from western Europe. We believe this means there will be no extreme differences culturally between our members. Belgium and France generally have the same score overall, there are some differences between the Netherlands, namely power distance, individualism, motivation towards achievement and uncertainty avoidance.

Power distance: Belgium and France have a very similar score except for the Netherlands who score very low. The Dutch prefer to focus on life over work, leading to a less competitive work environment.

Individualism: Dutch people prefer not to work against each other on a competitive basis.

Motivation towards achievement and success: Once again the Netherlands scores very low underscoring their focus on private life over professional.

Uncertainty avoidance: France and Belgium share a high score, Belgium especially. Belgium has 11 governments and thus needs a lot of rules and regulations. We also think this is a beneficial trait for teamwork. We like to look for compromises.

9 Result expectations/Deliverables

Expectations around results play an important role in keeping a clear vision on the scope of the project. Expectations can help you evaluate the eventual outcome of the project. Whether the deliverables set out to complete were achieved or changed.

9.1 Midterm result expectations

For our midterm report we were expected to complete a part of WP2 of this project. WP1 was already done before we started with the project.

The project began with an analysis of production potential (WP1). The volumes of organic materials available have been identified, key producers have been mapped out, and the current production processes thoroughly analyzed. This information is needed to start WP2.

Next, the focus will shift to production technologies (WP2). This phase involves mapping and evaluating the technologies used in existing facilities. It will assess the size and capacity of current plants and identify which fuels are most interesting for further developments such as biogas, ethanol, methanol, synthetic diesel and other alternative fuels. For every technology it is necessary to list up the pros and cons to find the ones that are the best to use in our case.

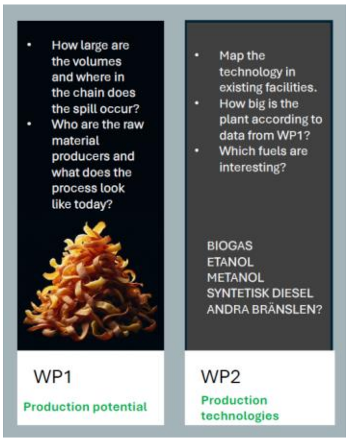

Figure 23. WP1 and WP2.

It is also necessary for our team to post regularly on a social media page. We have chosen to start an Instagram page.

9.2 Final result expectations

As we approach the end of our project, it's important to build further on everything we have done for the midterm report. The expectation for the final phase was to complete the main parts of WP2, which builds upon the earlier work we have done for the midterm report. During this semester, we have focused on researching further into our production technologies that could be used to convert potato waste into biofuels. This involved evaluating various reactor types, capacities, energy efficiency and how suitable they are for further processing.

We have also considered the possible applications of these technologies in real-life scenarios and how they could be used in different sectors.

In addition to the technical research, our team has been communicating our project's progress through social media. We regularly posted on our Instagram page to share insights and raise awareness about our project and the topic of sustainable energy from waste materials.

By the end of the project, we wanted to create a clear overview of the technologies we researched, the selection process and the reasoning behind our final choices. This will help the people who will work further on this process during the next work packages.

9.2.1 Extra deliverables

Apart from the deliverables given in work package 2, we also got familiar with some of the deliverables from work package 3. To be exact, we have completed 2 extra deliverables which we think are important to draw a final conclusion on which technology is more interesting.

Extra deliverable 1: Cost

One of the extra deliverables we worked on this semester was analyzing the cost of each technology. Understanding the cost is important when comparing different production methods, because it gives a realistic view of which options are economically feasible. Even if the technology performs well in terms of output or efficiency, it might not be a good option if the investment or operational costs are too high. By researching the estimated costs for construction and operation, we were able to get a better picture of which systems could be implemented in real-world situations.

Extra deliverable 2: Comparison

Another important extra deliverable we worked on was making a clear comparison between the different technologies. Having a good overview of all the options helps us to better understand which technology fits best in different situations. For example, some methods may be easier to operate or require less technical knowledge, while others might be more complex but have lower greenhouse gas emissions. By comparing things like environmental impact, ease of use and total costs side by side, we can make a better decision. This comparison is useful not only for our project but also for others who might want to use our research in the future.

9.3 Project expectations

After WP2, a technical-economic analysis (WP3) will be conducted. This will explore the resources needed for production, including an assessment of emissions and waste generation. It will also calculate both capital expenditure (CAPEX) and operational expenditure (OPEX). Various technical solutions will be compared to determine those that offer the lowest environmental impact, highest potential revenues, and most cost-effective investment opportunities.

Figure 24. WP3.

WP4: Realization

This phase focuses on turning the project into a practical and actionable plan. It involves reviewing opportunities for financial support, navigating legal and permitting requirements, and evaluating potential environmental impacts. A key task is selecting the most suitable business or organizational model for the deployment of this plant. Once identified, a detailed investment plan needs to be developed to ensure the project's viability and sustainability.

WP5: Dissemination

In this phase project data will be made publicly accessible to promote transparency around the project. Regular outreach activities, such as webinars, website updates, and publications, will keep stakeholders informed. Additionally, efforts will focus on building strong relationships with stakeholders and potential financiers to secure long-term support and collaboration.

Figure 25. WP4 and WP5.

10 Technologies

Below is an overview of the possible technologies that were investigated to produce biofuels from potato waste.

It is structured starting with the required steps for **pre-treatment** followed by an explanation of the **general process** and the type of reactors. The **outputs** resulting in the process are listed and the **advantages/disadvantages** are discussed. In addition, a cost analysis has been done between those last two. Finally, some **companies** that utilize the types of processes.

10.1 Pyrolysis – Biochar/syngas/bio-oil

Pyrolysis is a direct thermochemical conversion process (also known as thermochemical liquefaction) in which biomass undergoes thermal decomposition at elevated temperatures in an inert atmosphere. This process irreversibly alters the chemical composition of the biomass and is commonly used to convert waste into valuable chemicals.
The products of biomass pyrolysis include gases such as methane, hydrogen, carbon monoxide, and carbon dioxide, as well as bio-oil and char.
To maximize bio-oil production, fast or flash pyrolysis is used. This method involves heating organic waste to approximately 500°C for less than 10 seconds.

10.1.1 Pretreatments

The pyrolysis process requires two main pre-treatment steps, with two optional steps to improve continuous operation or overall efficiency.

Main steps:

Drying

Potato waste contains a high level of moisture, around 80%. The ideal range for pyrolysis is a moisture level below 10%. This can be achieved either by sun-drying for a couple of days or the faster method of oven drying for 48 hours at round 50°C. [3]

Grinding/milling

The PPW (Potato Peel Waste) that is fed into a pyrolysis reactor needs to be reduced in size to achieve the optimal level of heat transfer. In lab environment it was tested using a 1 mm screen. [3]

Optional steps

Screening

To ensure a good reactor performance the PPW should be homogenized, after the grinding step it is recommended to screen the PPW for consistent size. This prevents uneven residence time in the reactor. [3]

Biological prep

It is also possible to add PPW-FR (Potato Peel Waste Fermentation residue) into the reactor from ethanol production out of other processes. These were shown to yield similar bio-oil outputs compared to untreated PPW. [3]

Table 2 Pretreatment steps for Pyrolysis [3]

Step	Description	Purpose
Drying	Oven drying (for example 50 °C for 48 hours) or sun-drying	Reduce moisture content to <10% for efficient thermal decomposition
Grinding/Milling	Milled to <1 mm particle size	Ensures uniform heat transfer and better feed handling in reactors
Screening	Optional to homogenize size	Avoids inconsistent heating
Optional fermentation/hydrolysis residue treatment	PPW-FR (Potato Peel Waste – Fermentation Residue) from ethanol production can also be pyrolyzed	Increases overall feedstock utilization (cascade valorisation)

10.1.2 General process

Table 3. Examples of the stages that occur during pyrolysis. [3]

Temperature (°C)	**Event**
<100	Volatiles, including some water, evaporate. Heat-sensitive substances may partially decompose.
100	Water remaining absorbed in the material is evolved. Water trapped in crystal structure of hydrates may be evolved at somewhat higher temperatures. Some solid substances such as fats, sugars, and waxes may melt.
100–500	Organic molecules break down. Most sugar derivatives start decomposing at 160°C–180°C. Cellulose decomposes at approximately 350°C. Lignin starts decomposing at approximately 350°C and continues releasing volatile products up to 500°C. The decomposition products usually include water, carbon monoxide, and/or carbon dioxide as well as a large number of organic compounds. The nonvolatile residues typically become richer in carbon and form large disordered molecules, with colors ranging between brown and black.
200–300	When oxygen has not been excluded, the carbonaceous residue may start to burn in a highly exothermic reaction releasing carbon dioxide and/or monoxide. At this stage, some of the nitrogen still remaining in the residue may be oxidized into nitrogen oxides (such as NO_2 and N_2O). Sulfur and other elements (such as chlorine and arsenic) may be oxidized and volatilized.

The above image describes the different phases the pyrolysis process goes through at which temperature. Starting with the evaporating of moisture and the decomposing of the most heat-sensitive materials. Once the temperature rises above 100°C, organic molecules start to break down. When the temperature approaches 200°C sugars start to decompose. It is important that oxygen is excluded, this causes an exothermic reaction in the carbon rich residue releasing carbon dioxide and or monoxide. Around approximately 350°C Cellulose will also start to decompose. Finally, up to 500°C lignin starts to decompose followed by other volatile products.

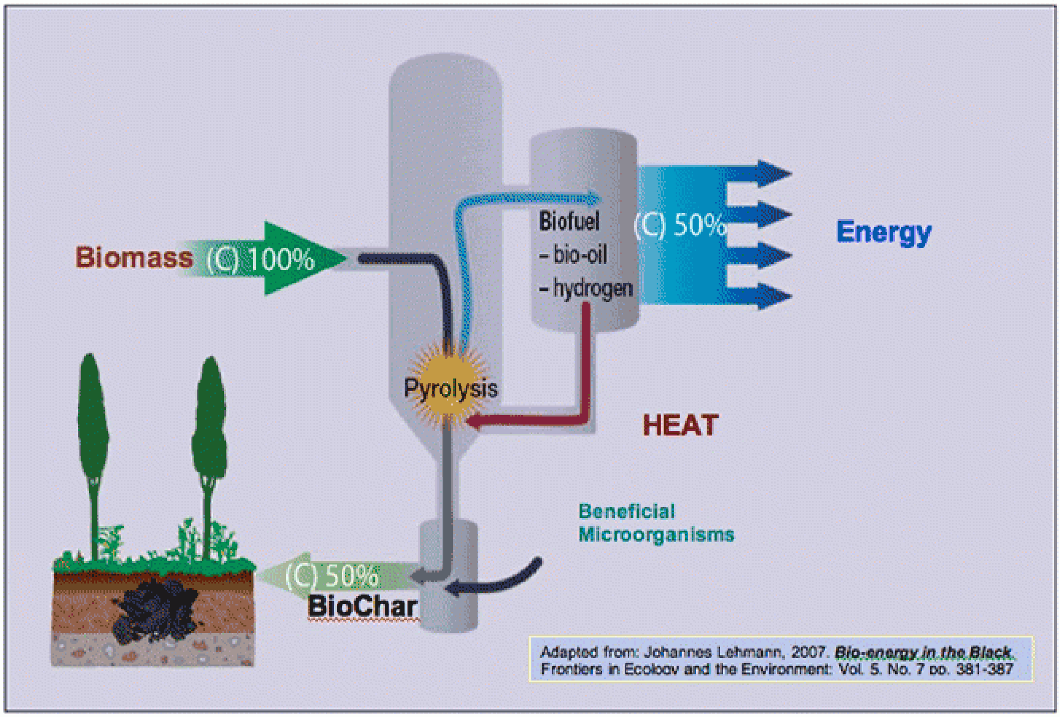

Figure 26. Pyrolysis process. [4]

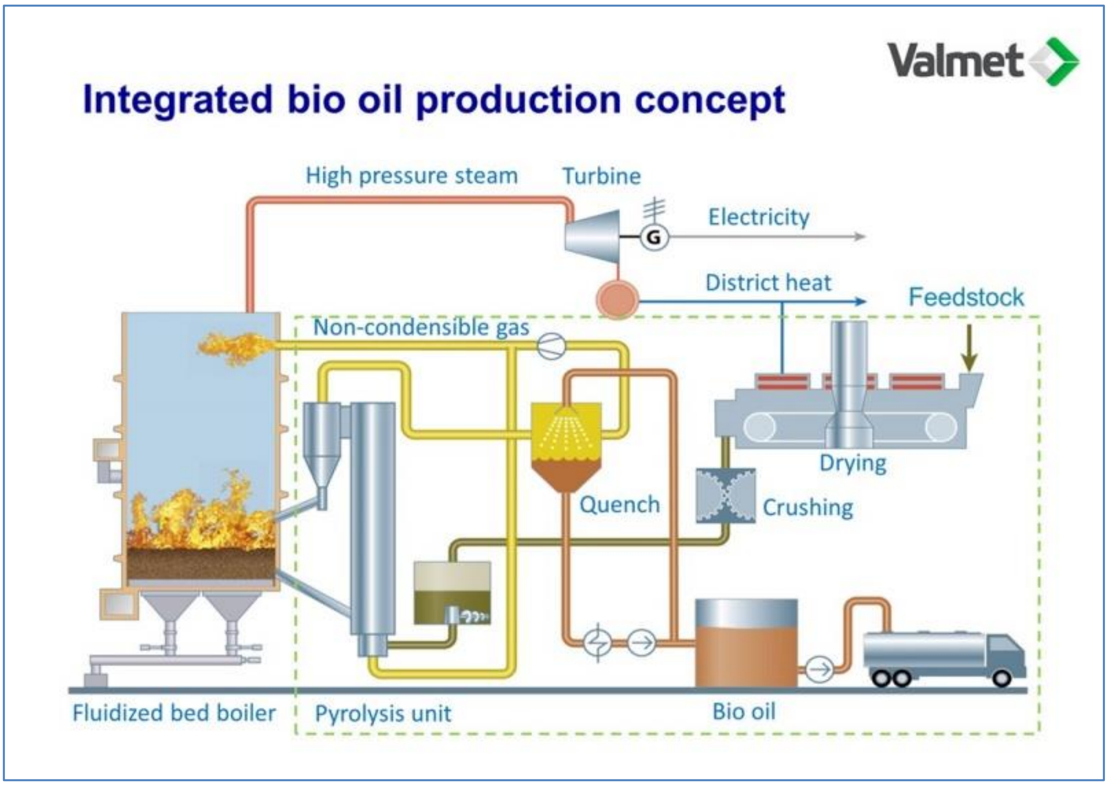

Figure 27. Example of pyrolysis. [5]

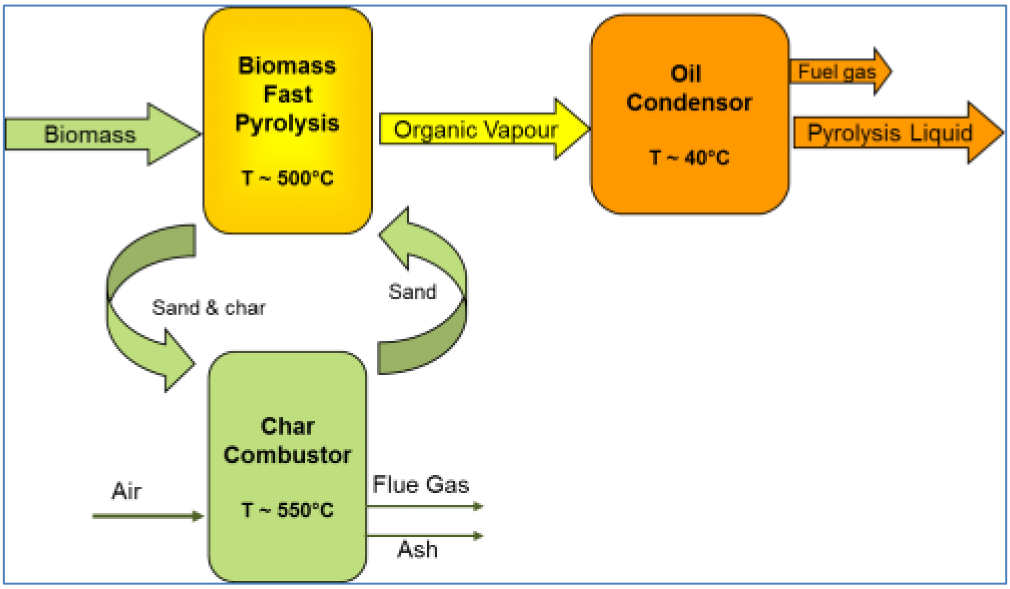

Figure 28. Fast or flash pyrolysis process. [6]

The above images show the general steps that the pyrolysis process goes through. First the feedstock is dried to reduce moisture content and milled to reduce the size of the feedstock. The increased homogeny improves heat transfer. The dried-out potato waste is then fed into a reactor which is deprived of oxygen. Inside the reactor the bio-waste is heated up to around 500°C where the pyrolysis reaction takes place and the outputs can be separated using a condenser.

Reactors

There are Three types of reactors that are best used depending on scale. First, for the smallest lab scale applications a fixed bed is sufficient. Second for pilot projects of small scale an Auger (screw conveyer) should be used for continuous feeding of bio-waste. Third, when small commercial scale is reached, a Rotary kiln or fluidized bed for better mixing and for all the waste to receive proper heating. Finally, for larger scale projects a circulating Fluidized bed (CFB) or moving bed due to its high throughput, there is also the recommended option of reusing the waste heat further increasing efficiency.

[7]

Criteria	Sub criteria	Kiln reactor			Fixed bed reactor			Fluidized bed reactor			Screw reactor		
Techno- economic	Heat transfer (HT)	1	3	5	0	0	1	7	9	10	5	7	9
	Feedstock particle size (FPS)	7	9	10	7	9	10	0	0	1	1	3	5
	Bio char residence time (BRT)	7	9	10	0	0	1	3	5	7	7	9	10
	Carrier gas flow rate (CGFR)	5	7	9	7	9	10	0	1	3	5	7	9
	Maintenance requirements (MR)	5	7	9	7	9	10	0	1	3	1	3	5
Industrial application	Scalability (SC)	7	9	10	0	1	3	9	10	10	3	5	7
	Feeding mode (FM)	1	3	5	0	0	1	3	5	7	3	5	7
Ecologic	Solar coupling ability (SCA)	3	5	7	9	10	10	7	9	10	0	0	1
	Emissions of harmful substances (EHS)	5	7	9	0	1	3	3	5	7	1	3	5

Figure 29 Decision Matrix of fuzzy values [7]

The above images show the different parameters of maturity of the reactor types based on different aspects that impact the efficiency of the reactor. Namely the Techno-economic, Industrial application and the Ecological aspect. Under the Techno-economic aspect, factors that should be considered are:

- Heat transfer (HT): influences the quality and consistency of the outputs
- Feedstock Particle size (FPS): Smaller size increases bio-oil production while larger size increases the amount of heavy carbon particles.
- Bio char residence time (BRT): lower time increases energy efficiency while longer time favors the cracking of long molecules of volatile products, which minimizes the bio-oil yield.
- Carrier gas flow rate (CGFR): Increased carrier gas velocity reduces secondary reactions
- Maintenance requirements (MR): Moving mechanical parts requires lubrication and can develop alignment issues.

Under Industrial application:

- Scalability (SC): The amount of feedstock that can be processed.
- Feeding mode (FM): Single batch, semi-batch and continuous mode.

On the Ecologic aspect:

- Solar coupling ability (SCA): So far only applicable and researched on a small scale.
- Emissions of harmful substances (EHS): Varies considerably depending on the type and composition of the feedstock, the operating conditions, the type and size of the pyrolysis reactor.

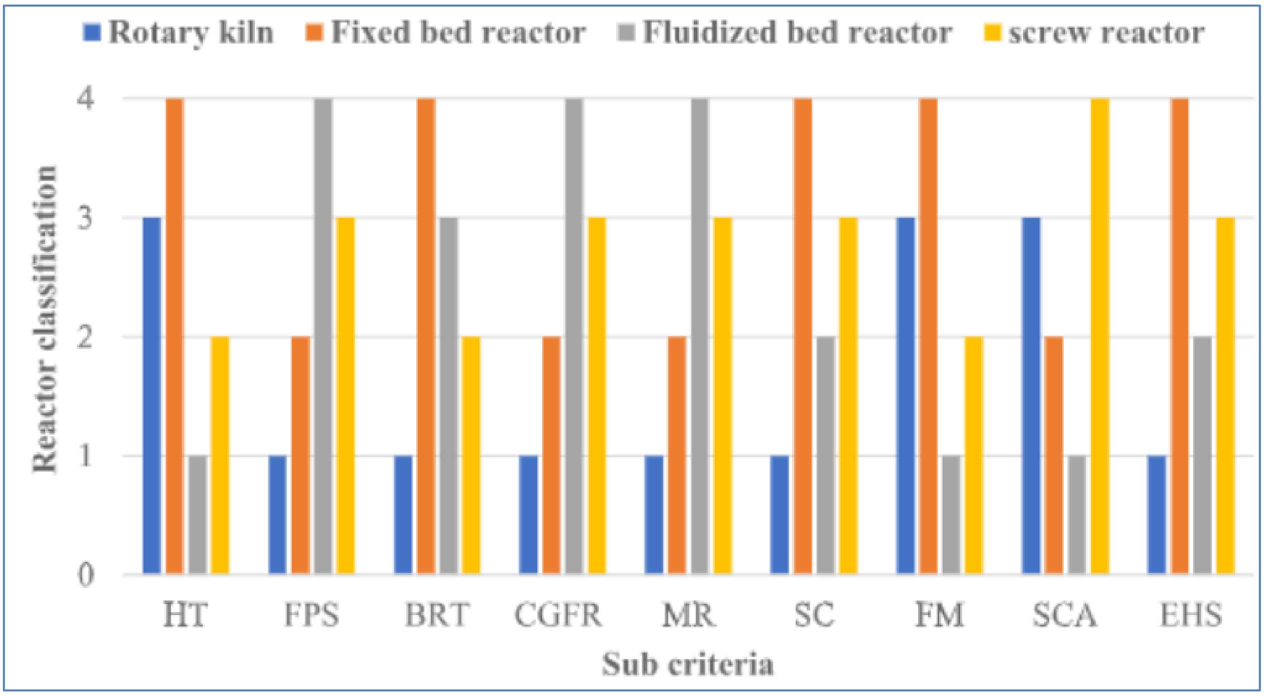

Figure 30 Sensitivity analysis results [7]

Table 4 Capacity's for different Pyrolisis reactors [3] [7]

Scale	Recommended Reactor	Key Features
Lab (<1 kg/h)	Fixed bed or batch	Simplicity, low cost, research-oriented
Pilot (1–10 kg/h)	Auger (screw conveyor)	Good for continuous feeding
Small-commercial (10–100 kg/h)	Rotary kiln or fluidized bed	Better mixing, heat uniformity
Large-scale (>100 kg/h)	Circulating fluidized bed (CFB) or moving bed	High throughput, energy efficiency, syngas reuse potential

If the total amount of potato waste is considered 22 600 000 kg and a CFB reactor is used and assumed that it operates at a 200 kg/h throughput. And a generous operational uptime of 7/7 365 days and 20h/day, capacity comes down to 200kg/h * 20 h* 365 days = 1,460,000 kg of potato waste throughput yearly per reactor. It must be considered that cost efficiency goes up with scale to a certain point where it starts to decrease again.

10.1.3 Output

Wt (percent by weight)

Table 5 Yield and energy content from Pyrolysis [3]

Product	Yield (% dry wt)	Energy Content (MJ/kg)
Bio-oil	~22.7%	~18 MJ/kg
Biochar	~30.5%	~20.3 MJ/kg
Syngas (est.)	~25–35%	~14 MJ/kg

Application

The three outputs from pyrolysis reaction:

- Bio-oil can be used in combination with diesel in a regular diesel combustion engine in a ratio of <20% bio-oil.
- Biochar is a carbon rich fertilizer.
- Syngas can be used in a regular gas combustion engine with a ratio of <20% syngas.

Cost analysis:

The cost of the reactor type depends on the scale required.

The fixed bed has the lowest throughput and is mostly used in lab settings.
An auger reactor is most often used for pilot projects.
A rotary kiln reactor can be used for small scale commercial applications.
Finally, a (circulating) fluidized bed should be utilized for larger scale commercial applications.

Table 6 Cost analysis for Pyrolysis

Reactor Type	Capital Cost Estimate (USD)
Fixed bed	>100,000€ [8]
Auger	$67,000 – $688900 [9]
Rotary kiln	$500,000 – $2.5 million [10]
(Circulating) Fluidized bed	$2 million – $20 million+ [11]

10.1.4 Advantages/Disadvantages

<u>**Advantages**</u>

Biowaste can be turned into three useful products.

- **Biochar**
  A solid carbon rich material that can be used as fertilizer.

- **Bio-oil**
  Liquid fuel that can be used for energy production, it could also be combined with diesel when refined at concentrations of <20% without the need for any alterations to the engine.

- **Syngas**
  Gas that consists mainly of carbon monoxide (CO), hydrogen (H_2), and carbon dioxide (CO_2), with small amounts of methane (CH_4) and other gases.
  Can be use for heat and electricity production.
  Can also be used in engines at concentrations of <20% with some modifications of the engine.

- **Carbon neutral**
  All carbon released was already present in the bio-waste, no new carbon is added.

- **Heat recovery**
  The pyrolysis process requires high temperatures, the waste heat of this process can be used for heating purpose of buildings in the area.

Disadvantages

- **High initial investment and operational costs**
    - Due to technical complexity of the machinery used in the process, requiring a precise control of temperature, pressure and oxygen levels on top of having to be able to resist high temperatures.
      The original investment is high.
    - Highly skilled personal and high maintenance costs on top of the high temperatures needed for the process,
      lead to high operational costs.

- **Energy intensive**
    - The high temperatures involved in the process require a lot of energy.

- **Limited adoption**
    - There are not a lot of plants using pyrolysis to convert bio-waste or similar into fuels. This means that there is limited knowledge and best practices to build on.

- Variable quality
    - A large factor in the quality of output is the consistency of the bio-waste being used. In the case of potato waste, the difference between peel and whole potato might have an impact on the quality of products.

- Environmental impact
    - Possible by products include volatile organic compounds requiring air purification systems
    - Another by product is ashes that are high in metal contents, these need careful disposal.

[12]

10.1.5 Companies

GFN Lieksa is a Green Fuel Nordic subsidiary operating a BTG Bioliquids fast pyrolysis bio-oil plant in Finland in the Kevätniemi in Lieksa. The GFN Lieksa Oy bio-oil refinery uses approximately 90,000 k-m3 of raw material per year, refined into 24,000 tons of bio-oil. [13]

Table 7 Companies that use Pyrolysis

Host Organisation	Country	Technology	Capacity kg feed/h	Capacity kg bio-oil/h	Applications	Status	Year
Twence/ EMPYRO	Netherlands	BTG-BTL - Rotating cone	5,000	3,250	Fuel	Operational	2014
Savon Voima Joensuu	Finland	VTT Fluid bed / riser	10,000	6,500	Fuel	Operational	2013

[14]

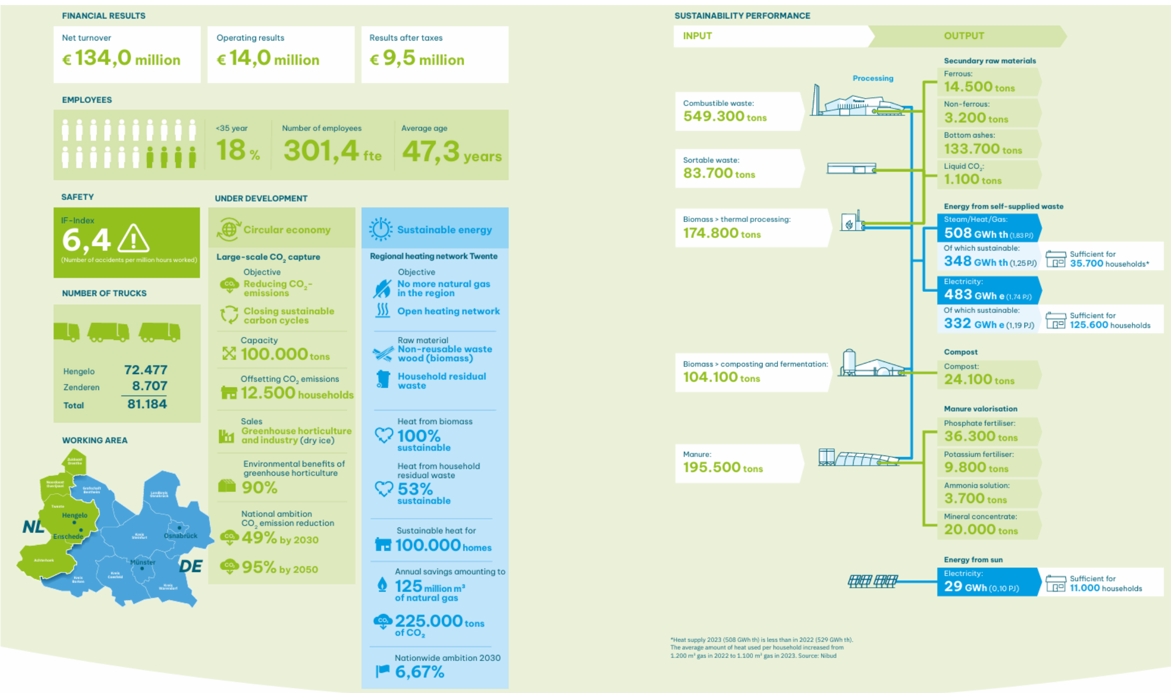

Figure 31. Twence: Located in the Netherlands Boldershoekweg 51. [5]

10.2 Gasification – syngas and further processing – bio methanol

This section evaluates the feasibility of using gasification to turn potato waste into syngas and then into bio methanol. First, let's explain what gasification is in general. It's a process that uses heat and a controlled amount of oxygen (or steam) to break down organic materials (like biomass) into a mix of gases, mainly carbon monoxide, hydrogen and carbon dioxide. This mix is called syngas. Once we have syngas, we can use it to make various fuels and chemicals, including methanol.

Bio methanol is methanol produced from biomass-derived syngas rather than from fossil fuel sources like natural gas. Bio methanol is considered a renewable fuel and is used in energy, transportation and as a feedstock for green chemicals. Its production involves gasification of biomass to form syngas, which is then converted into methanol using a catalyst. Compared to conventional methanol, bio methanol has a lower carbon footprint and supports decarbonization goals, especially in sectors such as marine shipping, automotive fuels (M85) and chemical manufacturing. [15]

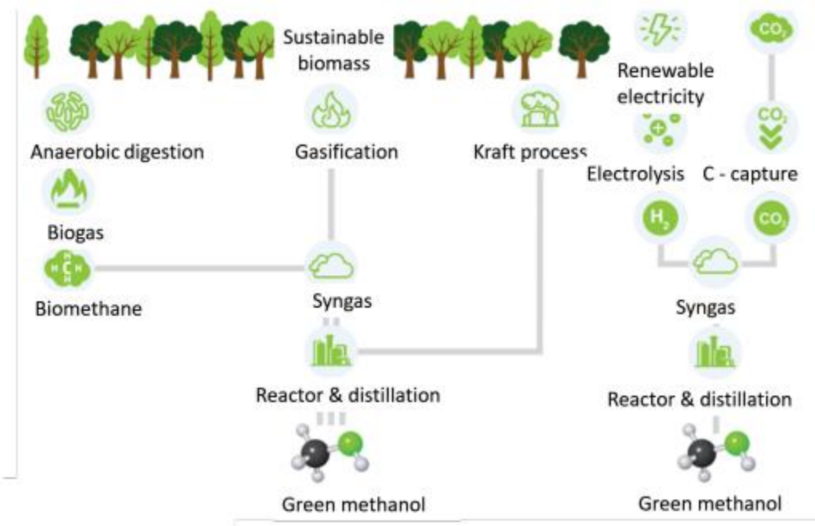

Figure 32. Visual of the basic principle of gasification [15]

10.2.1 Pretreatments

This table shows the most used pretreatments that happen before gasification:

Table 8. Pretreatments for gasification

Step	Description	Purpose
Drying	Oven drying (for example 50 °C for 48 hours) or sun-drying	Reduce moisture content to <10% for efficient thermal decomposition
Milling	Milled to <0.4 mm particle size	Ensures uniform heat transfer and better feed handling in reactors
Torrefaction	Using H/C and O/C, while increasing the relative content of fixed carbon and coalification degree of biomass at 200–320 °C	Raising the biomass' calorific value and energy while also reducing moisture content
Hydrothermal treatment	Thermochemical process transforming biomass into a high-carbon-solid (hydrocarbon) product, with some liquid byproducts (bio-oil mixed with water) and negligible gases	Increased yield of H_2, CO, and CH_4 Decreased yield of CO_2 Overall better syngas quality

[16] [17] [18]

The two most used methods are drying and milling because these methods are less energy intensive then torrefaction and hydrothermal carbonation. The pretreatment also depends highly on which gasifier is being used in the process. In the chapter "General process – syngas" we will go more in depth on this.

Drying [18]

Potato waste, like peels and rejected tubers from food processing, usually has a very high moisture content (sometimes over 75%). This makes drying an essential first step before any kind of conversion can take place. Drying reduces the water content to a level where the biomass can be gasified or further treated efficiently. In the case of potato waste, drying can be done using hot air dryers or waste heat from nearby industrial processes. If the moisture isn't removed, a lot of energy is wasted just evaporating the water during the gasification, which lowers the temperature inside the reactor and results in poor-quality gas and more tar. So, drying helps reduce energy loss and improve syngas quality when using potato waste.

Milling [17]

After drying, potato waste can be milled or grinded into smaller particles. This is especially important because dried potato material can be bulky and uneven. Milling improves the surface area and makes heat and reactions during gasification more efficient. Since potato waste is starch-rich and relatively soft compared to wood, it’s easier to grind, which also saves energy. When milled to an optimal size (around 0.4 mm), the material reacts better in the reactor, produces more gas and leaves behind less residue. In addition, if the potato waste is pelletized or densified after milling, it becomes easier to store and transport, especially in large-scale operations.

Torrefaction [17]

Torrefaction is useful for improving the energy content and storability of biomass. Since potato-based biomass has a high volatile content and low energy density, torrefaction (heating it to around 250–300°C in the absence of oxygen) helps remove moisture and light compounds while making the material more uniform and coal-like. The result is a dry, brittle and energy-rich solid that can be stored without spoiling and is easier to grind. For potato waste, torrefaction reduces the risk of microbial growth during storage and makes it perform better in gasifiers by lowering tar formation and increasing hydrogen(H_2) and carbon monoxide(CO) yields.

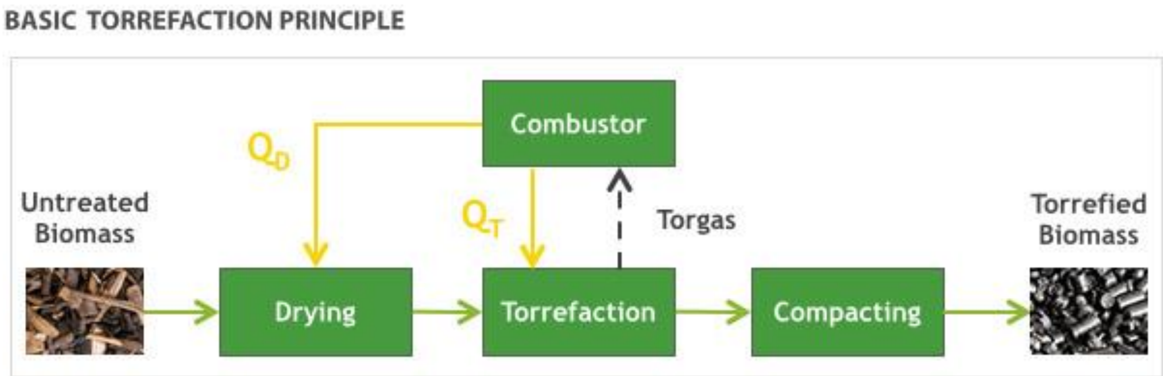

Figure 33 Process of torrefaction [19]

Hydrothermal treatment [17]

Because of its high moisture content, potato waste is very well-suited for hydrothermal treatment. This process uses hot, pressurized water to convert wet biomass into a carbon-rich solid called hydrochar. The best part is that drying isn't needed before this step. During hydrothermal treatment, the structure of the potato biomass is broken down and the result is a more energy-dense and chemically stable material. This makes the gasification of potato waste much more efficient. It also helps reduce the formation of tar and unwanted byproducts. For wet, starchy waste like potatoes, this is one of the most effective pretreatment methods.

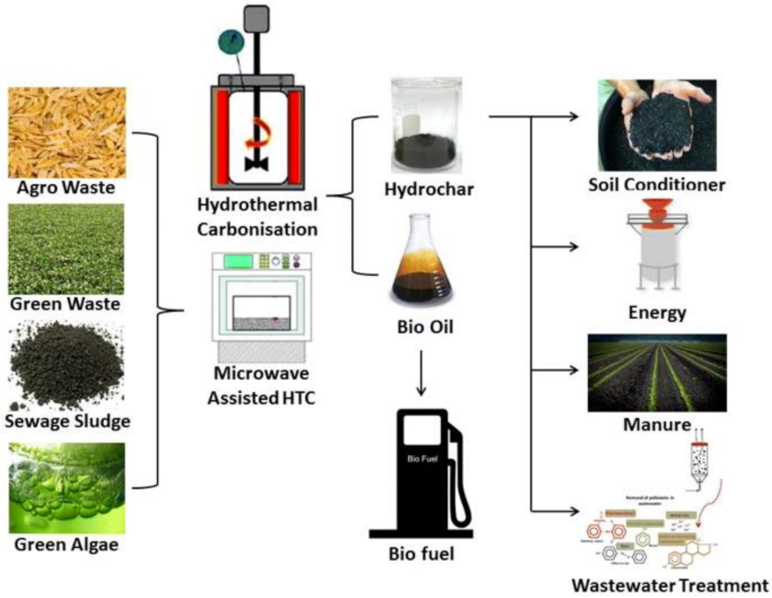

Figure 34 Process hydrothermal treatment. [20]

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10.2.2 General process

General Process of Biomass Gasification [16]

Gasification is a thermochemical process that partially oxidizes biomass at high temperatures (typically 800–1000 °C) to produce syngas. This gas is a combustible mixture of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and carbon dioxide (CO_2). This gas can then be used to either use as a fuel itself or it can be used to turn into different chemicals. Like we said before, we are looking into converting the syngas into bio methanol.

The main stages of the gasification process are:

Drying

- The biomass feedstock is heated, evaporating its remaining moisture content.
- No chemical change occurs but this step is critical for an efficient conversion.

Pyrolysis (devolatilization) [21]

- Biomass is thermally decomposed in the absence of oxygen.
- Produces volatiles (gases and tars) and solid char (carbon-rich residue).

$$PPW(biomass) \rightarrow char + HO_2 + CO + CO_2 + NO_2 + ash/tar + other\ chemicals$$

Oxidation (combustion) [22]

- A controlled amount of oxygen or air is introduced.
- Partial combustion of char and volatiles generates heat for endothermic reactions.

$$C + O_2 \rightarrow CO_2$$
$$C + 12O_2 \rightarrow CO$$

Reduction [23]

- In the lower oxygen zones, several gasification reactions occur:
  - Water-gas reaction: $C + H_2O \rightarrow CO + H_2$
  - Boudouard reaction: $C + CO_2 \rightarrow 2CO$
  - Steam reforming and methanation also play roles.
- These reactions convert remaining char and gases into syngas.

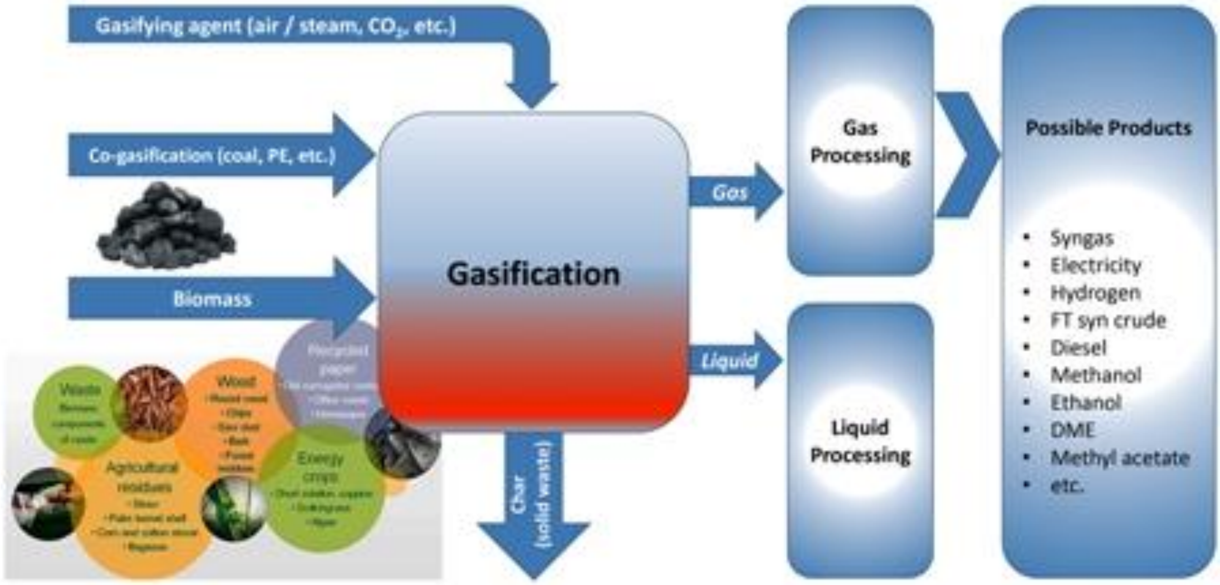

Figure 35. Biochemical process of gasification. [24] [25] [26]

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Reactors [16]

The reactor design determines heat transfer, residence time, mixing and tar production. All of these affect the gas produced by the gasifier.

Table 9. Reactors for gasification

Gasifier	Characteristics of syngas
Fixed-bed gasifier	Updraft gasifier: lower outlet temperature, low H_2 and C_nH_m content, high CO content, and high tar content, requiring complex purification treatment
	Downdraft gasifier: increased H_2 content, tar cracking through the high-temperature zone, reduced content, and high gas outlet temperature will reduce the efficiency of the generated gas
	Cross-flow gasifier: high tar content of gas, high gas outlet temperature, and low efficiency of gas production
Fluidized-bed gasifier	Fast gasification rate, higher gas production rate, stable temperature in the gasifier, less tar content in the produced gas but more ash content in the gas, high content of H_2 and CO with the particulate matter when blowing O_2
Entrained flow gasifier	High gasification temperature, high intensity, almost no tar in the outgoing gas, very low CH_4 and CO_2, high content of H_2, CO

Fixed-Bed Gasifiers

- Types: Updraft, downdraft and cross-draft.
- Advantages: Simple design, low maintenance and good for small-scale applications.
- Disadvantages**:** Limited scalability, high tar in some types (especially updraft).
    - Updraft: High tar content, suited to high-ash feedstocks.
    - Downdraft: Low tar syngas due to cracking in the hot zone.
    - Cross-draft: Less efficient overall, high tar and high outlet temperatures.

Fluidized-Bed Gasifiers

- Types: Bubbling, circulating and dual fluidized beds.
- Advantages: Better temperature control, high syngas yield, accepts varied biomass.
- Disadvantages: Higher ash in gas output, more complex equipment.
    - Bubbling bed: Even temperature, moderate tar but large bubbles may reduce efficiency.
    - Circulating bed: Improved mixing and residence time, less tar and CO_2, higher H_2 and CO.
    - Dual bed: Separate zones for combustion and gasification, high-quality syngas but early-stage technology.

Entrained-Flow Gasifiers

- Advantages: High temperature and conversion efficiency, low tar content.
- Disadvantages: Requires fine feedstock, high oxygen demand, expensive.
- Best for industrial-scale applications, especially when using pretreated biomass (torrefied or hydrothermally carbonized).

For gasification of potato waste, a bubbling fluidized-bed gasifier is generally the most suitable option. This type of reactor handles wet, low-density biomass like potato peels very well. This gasifier has a uniform temperature and good mixing quality inside the bed. This helps ensure that the feedstock is efficiently converted into syngas and it also keeps tar formation relatively low. Another big advantage is that the reactor is less prone to clogging, which is important when dealing with sticky and high-moisture materials like food waste.

However, if a proper pretreatment is done (such as drying, milling, torrefaction or hydrothermal carbonization) then a downdraft fixed-bed gasifier can also be a good option. These gasifiers produce syngas with very low tar content, which is ideal if the gas needs to be used directly in engines or burners. The key is that the potato waste needs to be dry and uniform, otherwise there is a high risk of clogging in the reactor.

The other reactor types are generally less suitable in this case:

- An updraft gasifier usually produces high levels of tar, especially when used with volatile-rich feedstocks like potato waste.
- An entrained-flow gasifier requires very dry, finely ground feedstock, which is not practical for raw potato waste without heavy pretreatments.

In summary:

- Without proper pretreatment → a bubbling fluidized-bed gasifier should be considered.
- With proper pretreatment → a downdraft fixed-bed gasifier becomes a good and efficient choice.

Capacity of the reactors [16]

Table 10. Capacity of reactors

Reactor type	Typical throughput	Suitability
Fixed-bed (Downdraft)	~20–200 kg/h	Small-scale, dry feedstocks
Fixed-bed (Updraft)	~200–1.000 kg/h	Small to medium scale, high ash
Fluidized-bed (BFB/CFB)	~1–500+ tons/day	Medium to large scale, flexible feed
Entrained-flow	>1,000 tons/day	Industrial scale, requires pretreatment

For choosing the right reactor we also must look at the capacity that the reactors could handle The potato spill from Ostrobothnia per year would be around 21,600,000 kg, that is the equivalent of 2790 kg/h. So, the best choice would be multiple bubbling fluidized-bed reactors if production is centralized. For small communities the best choice would be the fixed-bed downdraft reactor.

Effect of gasification agents [16]

The gasification agent directly determines the outcome of the chemical structure of the syngas so it is important to investigate them. The gasification agent also depends (just like the reactors) on what type of syngas we eventually want. We will discuss in the chapter of bio methanol what type of syngas we need to get high quality methanol.

Table 11. Gasification agents

Agent	Syngas characteristics	Pros	Cons
Air	Contains ~79% nitrogen → low H_2 and heating value. Produces a dilute syngas (4–7 MJ/Nm³).	Cheap and easy to use. No need for external gas supplies.	Low calorific value due to N_2 dilution.
Oxygen (O_2)	High CO and H_2 production, avoids nitrogen dilution, results in higher-quality syngas.	Higher energy density syngas, lower tar, and higher temperature reactions.	Costly due to need for oxygen separation or purchase.
Steam	Promotes H_2 production via water-gas and steam reforming reactions. Raises calorific value to 10–18 MJ/Nm³.	Produces hydrogen-rich, clean syngas. Good for fuel cells or synthetic fuels.	Needs external heat source; adds complexity to system.
CO_2	Enables Boudouard reaction → more CO. Reduces tar, promotes carbon conversion.	Useful for CO-rich syngas or carbon utilization schemes.	Lower calorific value overall; less commonly used in industry.
Air + Steam	Balances economy and syngas quality. Enhances H_2 production compared to air alone.	Widely used hybrid approach. Improves calorific value vs. air.	More complex system design.
O_2 + Steam	Produces the highest H_2 concentration and calorific value (LHV > 8 MJ/m³). Often used in advanced dual-stage or high-efficiency systems.	Excellent syngas for chemical synthesis or hydrogen production.	High cost due to both O_2 and steam generation.

Potato waste is high in moisture and volatiles and usually has a low heating value on its own. The gasification agent you choose should help:

- boost hydrogen production,
- handle the moisture content efficiently
- improve syngas quality without requiring extreme conditions.

Best Choice

According to the research, steam is highly effective for increasing H_2 production in the syngas via steam-reforming and water-gas shift reactions. This makes it ideal for feedstocks like potato waste that:

- already contain a lot of inherent moisture
- release volatile compounds that can be reformed with steam into useful gases.

Even better, using steam mixed with oxygen (O_2 + steam) results in:

- significantly higher H_2 and CO content,
- improved calorific value (up to 8.35 MJ/m^3)
- reduced tar levels compared to steam or air alone.

So, steam alone is great, and steam + O_2 is even better, especially if the system can handle the added complexity and cost.

Other Options

- **Air**: Very affordable and easy to implement but, introduces a large amount of nitrogen into the process which decreases the quality of the syngas and lowers its heating value. For potato waste this isn't ideal unless cost is a real concern.

- **Pure O_2**: Increases temperature and syngas quality but expensive and doesn't help as much with hydrogen production compared to steam. Not the best option for wet biomass like potatoes.

- **CO_2**: Helps convert carbon to CO via the Boudouard reaction but overall gas yield and heating value are lower. It's more useful in co-gasification setups or carbon recycling processes.

For potato waste, the best gasification agent is steam especially if the goal is to produce hydrogen-rich syngas. Even better results can be achieved using a steam + oxygen mix. The problem with this is that the setup is more complex and expensive. Air is okay if budget is a major problem, but it results in lower syngas quality. Pure oxygen and CO_2 are less suitable on their own unless the system is highly specialized.

Analysis

Environmental Sustainability

Greenhouse gas (GHG) emissions reduction potential: During the process the carbon that comes out of the process gets captured thus lowering the greenhouse gas compared to direct combustion. However, the process is not completely free of emissions.

Energy efficiency (energy output/input ratio): CO_2 gasification has an overall energy efficiency of 55% and higher. [27]

Water consumption and pollution: The water consumption really depends on the type of gasifier that is used. Steam gasification has a really high water use compared to the other ones. The advantage of steam gasification is that you get a syngas that contains a high content of hydrogen. If we want to convert the syngas further into bio methanol it is important that we have a high CO/H_2 ratio. So, in that case steam gasification is the most interesting, leading to a high water consumption. [28]

Land use impacts: The process does not require large installations, so the land use impact is minimal.

Waste reduction potential: Even after the potato peels are used in the process, the waste product from gasification can be reused. For example, tar can be used for building materials. There are still lots of undesired by products such as methane and higher hydrocarbons.
[29]

Carbon footprint across lifecycle: Since we are not using any types of coal or cokes the carbon footprint of this process stays fairly low.

Economic Viability

Capital investment requirements: Gasification is a very advanced technology making it one of the pricier processes. The potatoes also need some pretreatment due to the high moisture content making it more expensive as well.

Operating costs: This process involves lots of maintenance due to the tar build up. The potatoes need to be checked on their condition to know how much oxygen/steam/heat needs to be added so I would say this is also more expensive compared to other methods.

Revenue potential: The main revenue process will come from reserve heat and electricity/methanol from the syngas. The waste can also be used to sell to building companies. The revenue that it generates depends highly on the current energy market.

Payback period: Between 5-15 years, depending on the properties of the feedstock and the temperatures etc. being used. [30]

Market readiness: Gasification of potato waste is possible, but it is not widely adopted. For this method mainly woodchips are used.

Scalability: The scalability is no issue with gasification. There are small scale gasifiers available on the market for smaller communities.

Technical Feasibility

Technology readiness level (TRL): So, the number of TRL that I see returning a lot is 5-7. [31]

Process complexity: As I said before, this is an advanced technology and the application on potato waste is still new, so this is complex process

Conversion efficiency: The cold gas efficiency is at least 65%, some exceeding up to 80%. [32]

Yield potential: Syngas from gasification generally creates a gas with a higher energy content than pyrolysis. [33]

Infrastructure requirements: Infrastructure includes feedstock collection and pre-treatment installations, gasifier(s) and power generation systems.

Adaptability to different potato waste streams: The installation can handle any type of potato waste streams if it has gone through a good pre-treatment.

Social Considerations

Job creation potential: Gasification projects can create jobs in construction, operation and waste management.

Rural development opportunities: Small scale gasifiers would be good for multiple potato farmers to dispose of their waste and make syngas out of it to sell.

Energy security contribution: Syngas can be used to create electricity or hydrogen which the people around the plant can use for their own households which would be great for remote areas.

Public acceptance: Accepted if there is a lot of transparency being used on the project.

Regulatory compliance: If the waste management is done properly, this won't really be an issue.

Further processing of syngas into bio methanol:

We have just seen that potato waste is a viable source to produce synthetic gases. These gases can be processed to produce different liquid fuels, but in this chapter, we will mainly be focusing on converting the syngas to bio methanol. However, before we get our bio methanol, we first need to complete some stages.

You can see the recap of these stages:

Table 12 Stages for bio methanol production

Stage	Process	Key purpose
Pre-purification	Cyclones, tar reforming, acid gas scrubbing	Clean syngas, protect catalyst
Methanol synthesis	Cu/Zn catalyst reactor	Convert syngas to methanol
Post-purification	Distillation, rectification	Achieve ≥99.85% methanol purity

For more clarity here is the general process for creating bio methanol:

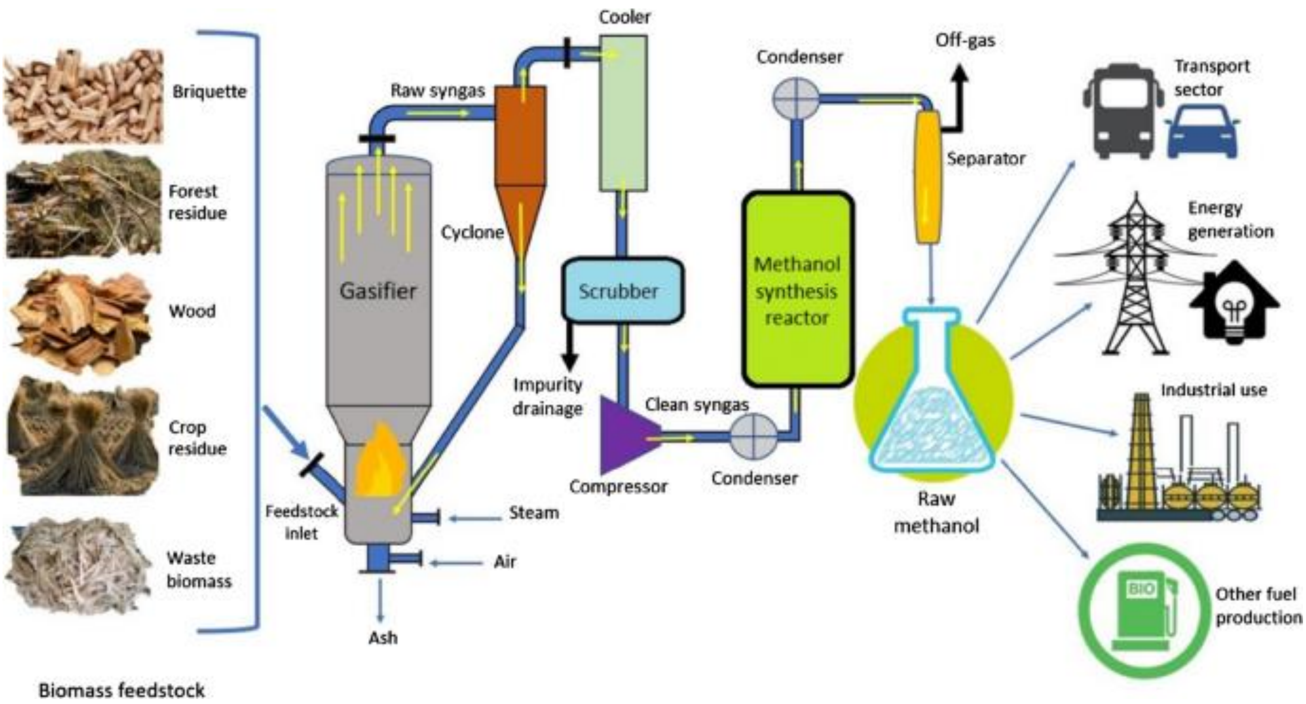


Figure 36: Bio methanol general process. [34]

Purification

The part before the gasification is called pre-purification. It is an important phase because of lots of particles and tars or sulphur components.

But before everything we need to know the composition of those syngas.

Syngas composition [35]:

The syngas derived from gasification of wet biomass such as potato waste typically contains:

- 35–45% hydrogen (H_2),
- 25–35% carbon monoxide (CO),
- 15–25% carbon dioxide (CO_2),
- trace amounts of methane (CH_4) and nitrogen (N_2)
- particles and tar

We still must keep in mind that the composition of the gas stream is influenced by the operating parameters of the gasifier, and some gasification processes are more suited than others to the production of a gas for methanol synthesis.

This composition is a big part of the factors with syngas composition from feedstock and final product sensitivity which influence the sequence and selection of the several stages in the pre-purification processus.

However, in our case we are talking about the purification of syngas produced from potato waste and the bio methanol to be produced. That is why the most common steps involved are contaminants removal and every kind of contaminants needs a special process so here is a table that present all the different methods.

Table 13 Pre-Purification processes

Purification process	Contaminants removed	Method	Advantages	Disadvantages
Cyclone Separation [36]	Particulates (ash, char)	Utilizes centrifugal force to separate solid particles from the gas stream.	Simple design; low maintenance; effective for large particles.	Ineffective for fine particles; may require additional filtration.
Water scrubbing [36]	Fine particulates, ammonia, chlorides	Gas is passed through a liquid to absorb contaminants.	Effective for soluble contaminants; can handle multiple pollutants.	Generates wastewater; energy-intensive due to gas cooling.
Activated carbon Adsorption [36]	Mercury, trace metals	Adsorption of contaminants onto activated carbon surfaces.	High removal efficiency; operates at low temperatures.	Carbon replacement and disposal required; less effective at high temperatures.
Catalytic hydrolysis [36]	COS (carbonyl sulphide)	Converts COS to H_2S using catalysts, facilitating subsequent removal.	Enhances sulphur removal efficiency; operates at moderate temperatures.	Requires precise temperature control; catalyst deactivation over time.
Acid gas removal (AGR) [36]	H_2S, CO_2	Chemical solvents (e.g., amines) absorb acid gases from syngas.	High selectivity; can achieve low contaminant levels.	Solvent regeneration needed; potential solvent degradation.
Water-Gas Shift (WGS) Reaction [36]	CO	Converts CO and H_2O to CO_2 and H_2, enhancing hydrogen yield.	Increases H_2 concentration; essential for hydrogen-rich syngas.	Requires catalyst; sensitive to sulfur poisoning.
Rectisol process [35]	H_2S, CO_2, COS	Physical absorption using cold methanol as solvent.	High removal efficiency; suitable for low-temperature operations.	High energy consumption for solvent refrigeration; complex operation.

Hot gas filtration **[37]**	Particulates, tars	High-temperature filters remove solids without cooling the gas.	Maintains gas temperature; reduces energy losses.	Filter material limitations; potential for filter fouling.
Bio-Diesel scrubbing **[38]**	Organic contaminants (e.g., tars)	Uses biodiesel as a solvent to absorb organic impurities.	Renewable solvent; effective tar removal.	Solvent recovery needed; potential solvent degradation.

For more information we can now focus on details with the commons processus.

Particulates removing technologies

<u>Cyclones</u>:

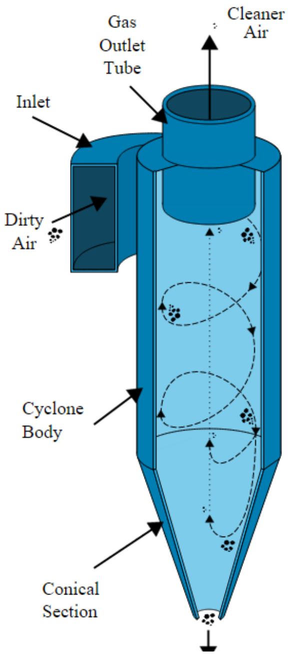


Figure 37: Cyclone separator [36]

Cyclone separators are often the first step in syngas purification. These devices use centrifugal force to remove solid particulates such as ash, char, or residual biomass that result from the gasification of potato waste. As syngas enters the cyclone tangentially, it spins rapidly, and the heavier particles are pushed outward to the walls and collected at the bottom, while the cleaner gas exits through the top. Cyclones are widely used due to their simple design, low maintenance, and ability to operate at high temperatures. However, they are mostly effective at removing larger particles (greater than 10 micrometres). Their efficiency typically ranges from 70-95% depending on the particle size and cyclone design [36]Also, the cyclone performance is influenced considerably by cyclone height, diameter and shape. [39]

<u>High-Temperature Filtration</u>:

Hot gas filtration is used to remove fine particulates and residual tars from syngas at high temperatures, typically between 400 and 900°C. This allows for cleaning without cooling, preserving thermal energy in the gas. The system uses ceramic or sintered metal filters that physically trap particles while allowing the gas to pass. This method is especially useful in integrated biomass-to-liquid processes, as it maintains system efficiency and prevents downstream equipment from fouling. The removal efficiency is very high, generally >99% for particles larger than 1 µm [40] [41].

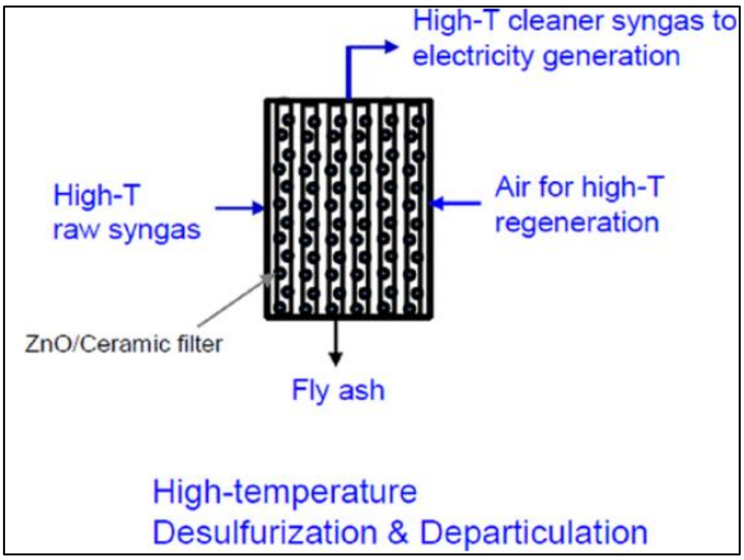


Figure 38 High-temperature filtration. [40]

Water Scrubbing

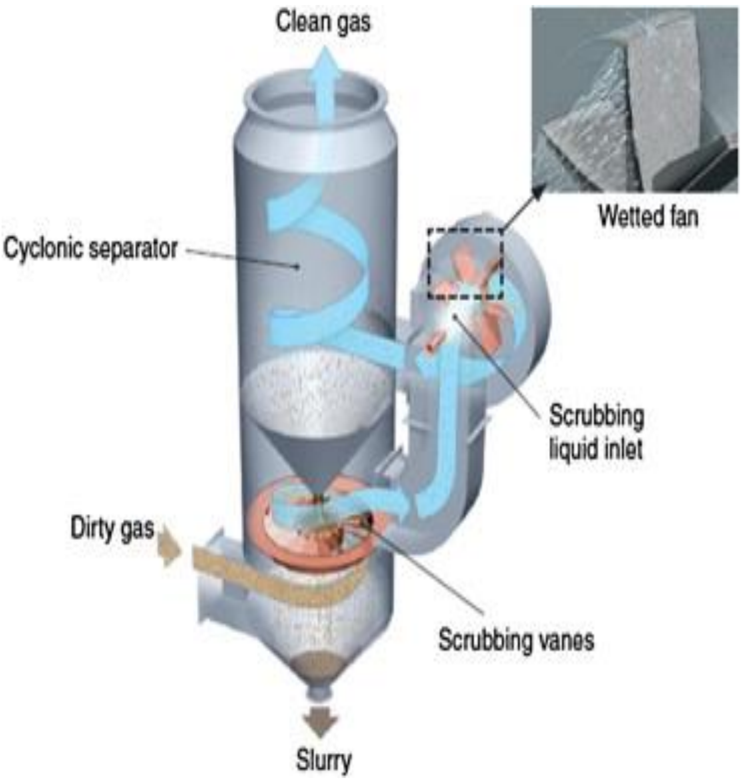


Figure 39. Wet scrubber [40]

Wet scrubbers are used to clean syngas by absorbing soluble contaminants into a liquid—often water or a mild alkaline solution. In this process, syngas is bubbled or sprayed through the liquid, where substances such as ammonia (NH_3), hydrogen chloride (HCl), and fine particulates dissolve or attach to the liquid. This method is effective for a broad range of pollutants, especially acidic gases and dust, and is often used downstream of cyclone separation. The efficiency of wet scrubbers can reach 80–99%, but they also produce wastewater that requires treatment, and the gas must be cooled before scrubbing, which reduces energy efficiency. [36] [40]

Activated Carbon Adsorption

Activated carbon adsorption is particularly useful for the removal of trace contaminants like mercury, cadmium, and other volatile metals, which are present in very low concentrations but can poison methanol synthesis catalysts. The process involves passing syngas through beds of activated carbon, which has a high surface area that traps and holds contaminants. This method is known for its high removal efficiency, often exceeding 90% for mercury, and it operates effectively at low to moderate temperatures. However, the carbon must be replaced or regenerated periodically, and it may not be effective at very high temperatures [40].

Bio-Diesel Scrubbing

Biodiesel scrubbing is a novel and environmentally friendly approach to removing tar and heavy organic compounds from syngas. It works by absorbing these contaminants into biodiesel, which has a strong affinity for large hydrocarbons. This process is particularly beneficial when working with high-tar feedstocks like wet or unprocessed potato waste. Biodiesel scrubbing can achieve 80–95% removal efficiency, depending on the contaminant load and flow conditions. It also offers a renewable solvent alternative, although challenges include solvent recovery and potential biodiesel degradation over time [38].

Gas composition removing technologies

Catalytic Hydrolysis

Catalytic hydrolysis is a chemical pretreatment used to convert carbonyl sulphide (COS), a common impurity in syngas, into hydrogen sulphide (H_2S), which can be removed more easily using acid gas removal systems. This reaction occurs over a catalyst, typically alumina-based, and requires moderate temperatures (200–300°C). The process helps reduce the sulphur burden before the main sulphur removal units. Conversion efficiency is usually between 80–95%, depending on gas composition and catalyst condition. This step is critical because sulphur compounds are highly toxic to the copper-based catalysts used in methanol synthesis (*Chiche et al., 2013*).

Acid Gas Removal (AGR)

Acid gas removal is a crucial step in purifying syngas for bio methanol production. It primarily targets hydrogen sulphide (H_2S) and carbon dioxide (CO_2), both of which interfere with catalyst performance. One common AGR method involves chemical absorption using amine-based solvents like monoethanolamine (MEA). These solvents chemically bind to acid gases and can later be regenerated to release and recover the gases. AGR systems are highly effective, achieving >99% removal of H_2S and around 90–95% for CO_2, making them essential for producing clean syngas [36].

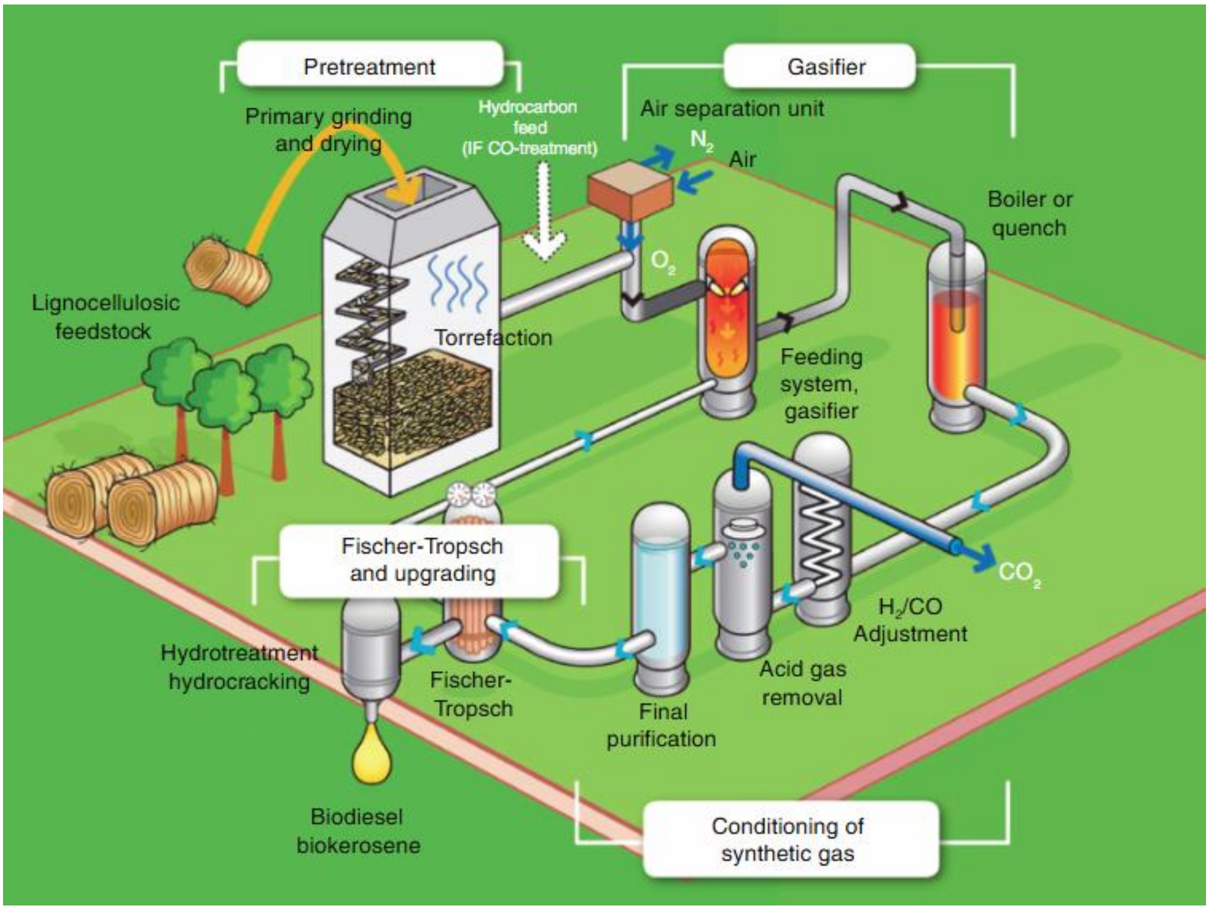
Water-Gas Shift (WGS) Reaction

The Water-Gas Shift (WGS) reaction is a vital chemical step used to adjust the hydrogen-to-carbon monoxide ratio in syngas before it undergoes methanol synthesis. During this process, carbon monoxide (CO) reacts with steam (H_2O) to form carbon dioxide (CO_2) and additional hydrogen gas (H_2). The reaction is slightly exothermic and is typically conducted in two stages: a high-temperature shift (around 350–450 °C) using iron-based catalysts, followed by a low-temperature shift (200–250 °C) using copper-based catalysts for more complete conversion. This adjustment is essential because methanol synthesis requires a precise stoichiometric ratio of CO, CO_2, and H_2, and raw syngas from biomass like potato waste often contains excess CO and insufficient hydrogen. The WGS reaction can improve hydrogen content significantly, with conversion efficiencies typically exceeding 90% under optimal conditions. However, the process also produces CO_2, which must be subsequently removed in downstream acid gas removal units [35] [42]

Rectisol Process

The Rectisol process is a physical absorption method that uses chilled methanol (typically at -40°C) to absorb impurities from syngas. It is especially effective at removing a wide range of acid gases, including H_2S, CO_2, and COS, along with trace amounts of tars and hydrocarbons. Due to its low-temperature operation, Rectisol offers very high removal efficiencies, greater than 99.5% for sulphur compounds and CO_2, and is often used in high-purity applications like methanol or hydrogen production. However, it is energy-intensive because it requires extensive cooling and refrigeration [35].

Examples of full pre-purification processes



Pretreatment
Gasifier
Primary grinding and drying
Hydrocarbon feed (IF CO-treatment)
Air separation unit
N_2
Air
Boiler or quench
O_2
Lignocellulosic feedstock
Torrefaction
Feeding system, gasifier
Fischer-Tropsch and upgrading
CO_2
H_2/CO Adjustment
Hydrotreatment hydrocracking
Fischer-Tropsch
Final purification
Acid gas removal
Biodiesel biokerosene
Conditioning of synthetic gas

Figure 40. [35]

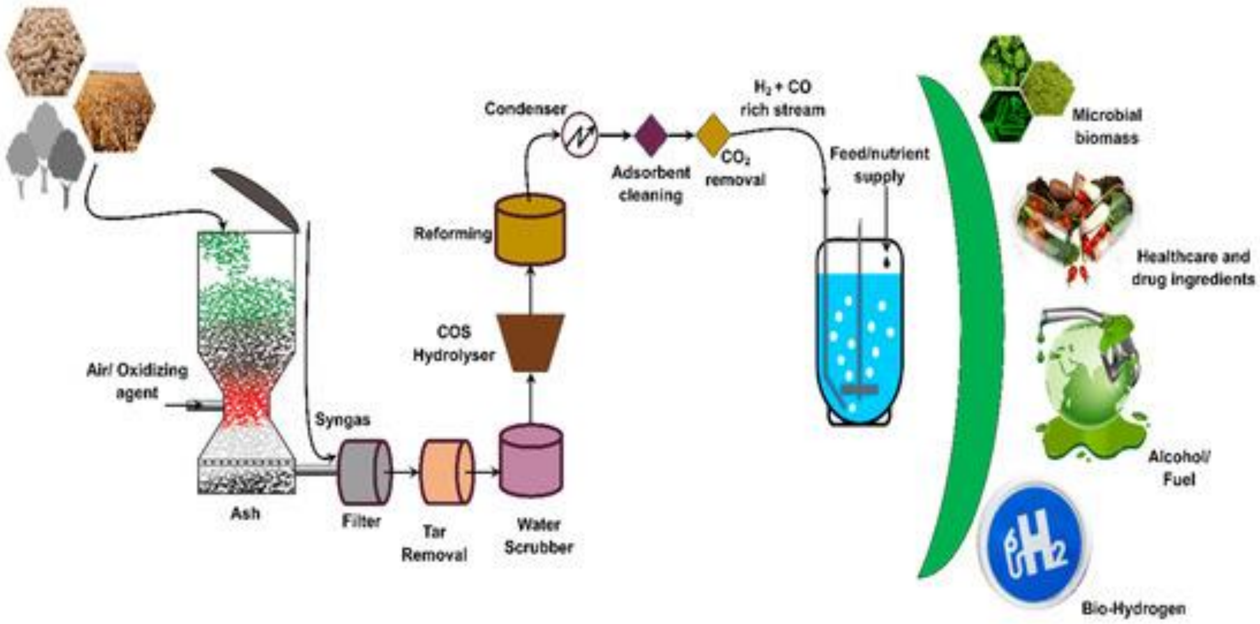
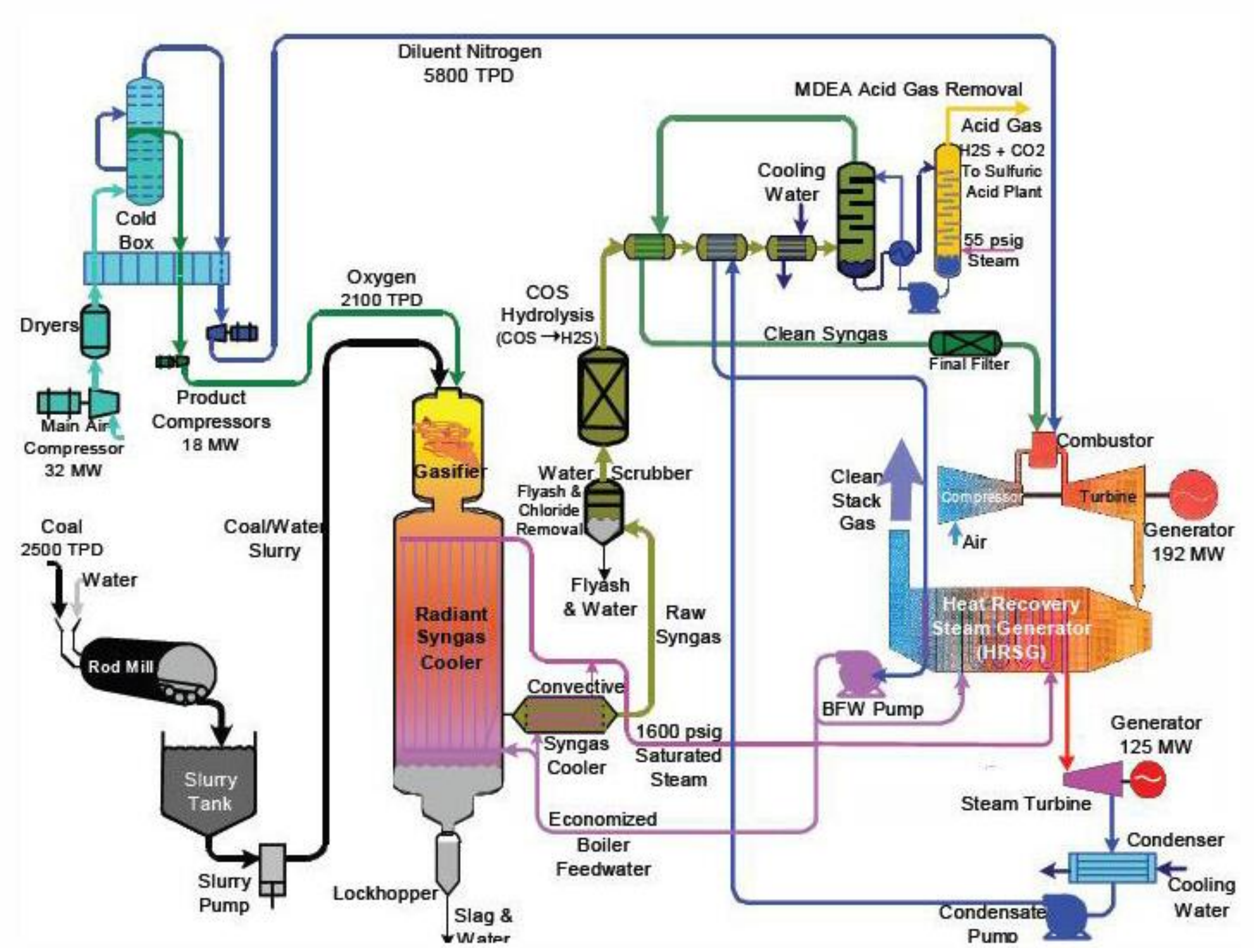

Condenser
H_2 + CO
rich stream
Adsorbent
cleaning
CO_2
removal
Feed/nutrient
supply
Reforming
COS
Hydrolyser
Air/ Oxidizing
agent
Syngas
Ash
Filter
Tar
Removal
Water
Scrubber
Microbial
biomass
Healthcare and
drug ingredients
Alcohol/
Fuel
Bio-Hydrogen

Figure 41. [43]



Diluent Nitrogen
5800 TPD
MDEA Acid Gas Removal
Acid Gas
H2S + CO2
To Sulfuric
Acid Plant
Cooling
Water
55 psig
Steam
Cold
Box
Oxygen
2100 TPD
COS
Hydrolysis
(COS → H2S)
Clean Syngas
Final Filter
Dryers
Main Air
Compressor
32 MW
Product
Compressors
18 MW
Combustor
Gasifier
Water
Scrubber
Flyash &
Chloride
Removal
Clean
Stack
Gas
Compressor
Turbine
Generator
192 MW
Air
Coal
2500 TPD
Water
Coal/Water
Slurry
Flyash
& Water
Raw
Syngas
Heat Recovery
Steam Generator
(HRSG)
Rod Mill
Radiant
Syngas
Cooler
Convective
Syngas
Cooler
BFW Pump
1600 psig
Saturated
Steam
Generator
125 MW
Slurry
Tank
Steam Turbine
Economized
Boiler
Feedwater
Condenser
Cooling
Water
Slurry
Pump
Lockhopper
Slag &
Water
Condensate
Pump

Figure 42. [36]

Creation of Bio methanol

The production of bio methanol from potato waste involves a series of thermochemical and catalytic processes that transform agricultural residues into a valuable renewable fuel. The first step is gasification, where dried potato waste is subjected to high temperatures (typically 800–1,000 °C) in a controlled atmosphere, often with oxygen or steam, to produce synthesis gas (as studied above). This syngas primarily contains carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), and traces of methane, tars, and impurities. The choice of gasifying agent is critical: while air is cheaper, it introduces nitrogen into the syngas, diluting it and making it unsuitable for methanol synthesis. Instead, oxygen-blown or steam gasification is preferred to produce a concentrated, nitrogen-free gas mixture [35] [42].

After gasification, the syngas undergoes pre-treatment and purification. This conditioning is essential to reach the ideal stoichiometric ratio for methanol synthesis, typically around H_2:CO = 2:1. Once purified, the syngas enters the methanol synthesis reactor, where it reacts over a copper-zinc oxide-alumina catalyst at temperatures of 200–280 °C and pressures of 50–100 bar [12] [43] The key reaction is:

$$CO+2H_2 \rightarrow CH_3OH$$

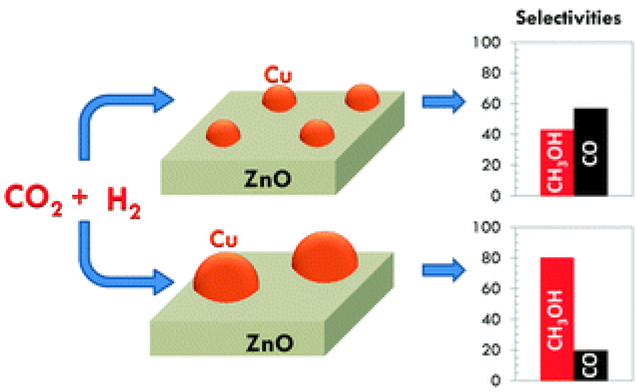


Figure 43. Chemical reaction of gasification. [44]

Additional side reactions involving CO_2 can also occur, enhancing the carbon utilization efficiency. Finally, the crude methanol is separated from unreacted gases through distillation and condensation, resulting in refined bio methanol, ready for use as a low-emission fuel or chemical feedstock. This pathway not only valorises food waste but also offers a sustainable alternative to fossil-derived methanol in alignment with circular economy goals [40] [36] [45].

After the reaction, the product stream contains methanol along with unreacted gases. The unreacted gases are then separated from the methanol using distillation. This final purification process ensures that the final product is a pure form of methanol/bio methanol.

Post-purification

The aim of post-purification is adjusting syngas composition and purity.

Once methanol is synthesized from syngas, the product is not yet pure. The crude methanol contains:

- Water
- Dissolved gases (CO, CO_2, H_2, N_2)
- Higher alcohols (e.g., ethanol, propanol)
- Esters and ketones (depending on impurities in syngas)
- Trace sulphur/nitrogen compounds

To produce Grade AA methanol (>99.85% purity), the following post-purification steps are required:

Table 14 Post purification steps for bio methanol. [46] [47] [48] [49]

Purification process	Contaminants removed	Method	Advantages	Disadvantages
Cooling and condensation	Crude methanol vapor	Heat exchangers and flash drums	Efficient initial recovery of liquid methanol; enables syngas recycling	Requires precise temperature control; some methanol remains in gas phase
Gas–liquid separation	Non-condensable gases (CO, CO_2, H_2, N_2)	Flash tanks or knockout pots	Prevents contamination of methanol in distillation; simple and low-maintenance design	Incomplete separation may still leave trace gases in the liquid
Crude methanol distillation	Water, light ends, fuel oils	Fractional distillation with decanter and main column	Removes major impurities; separates methanol effectively	Energy-intensive; requires careful design and operation to avoid methanol loss
Methanol rectification / final polishing	Trace impurities, azeotropes	High-efficiency rectification with reflux control; azeotropic/extractive distillation	Achieves high-purity methanol (≥99.85%, Grade AA); adaptable for various impurity profiles	Complex setup, additional solvents may be required for azeotropic/extractive steps
Storage and quality control	Potential storage contamination	GC-MS or HPLC analysis; storage in stainless steel or aluminium tanks	Ensures product meets specifications; prevents contamination during storage	Analytical equipment cost; tank material selection critical for long-term purity

10.2.3 Output

Table 15 Energy yield and content. [50] [51] [52] [53]

Product	Yield (% dry wt)	Energy Content (MJ/kg)
Syngas	≈ 70-90%	4,5 MJ/kg
Bio methanol	≈ 5-20%	15-18 MJ/kg

There was no specific research for yield and energy content numbers for bio methanol from potato waste. The numbers that you see here are mainly from biomass from the rice and the wood sector. Since potato waste has a high moisture content, the yield and energy content would probably be on the lower end of these numbers we found.

One of the main uses of bio methanol is as a fuel. It can be mixed with gasoline (for example, in M85, which is 85% methanol and 15% gasoline) and used in regular engines without needing big modifications. It's also used in fuel cells, which can generate electricity without burning the fuel, making it a lot cleaner. Marine fuel can be replaced with bio methanol as well, which is interesting since the heavy oils that are now used are not clean at all and emit lots of greenhouse gasses in the atmosphere. There's even the possibility of using it for aviation, especially in synthetic fuels. It can also be used in power plants or small generators to produce electricity.
[54]

Another big application for bio methanol is as a chemical feedstock to further refine into other chemicals.
For example:

- **Formaldehyde**, which is used to make plastics and resins.
- **Acetic acid**, used in making vinegar, solvents, and some plastics.
- **MTBE (methyl tert-butyl ether)**, which is added to gasoline to improve performance.
- **Dimethyl ether (DME)**, a fuel that can replace LPG and is also used in spray cans.
- Other chemicals like methyl methacrylate and dimethyl terephthalate that are used in products like acrylic glass and polyester.

Bio methanol is also useful for producing hydrogen. Hydrogen is important for the use in fuel cells and other clean technologies. Since hydrogen gas is not easy to transport or store, bio methanol can be transported. Later the methanol is to be turned into hydrogen, so it can be directly used in the application site.

Finally, bio methanol helps with carbon capture. It can be produced by using CO_2 and hydrogen. Instead of just releasing CO_2 into the air, we can turn it into fuel. That's a big step towards fighting climate change.

Syngas is a very versatile resource that can be used for lots of applications. The biggest being electricity, hydrogen, synthetic natural gas and liquid fuels (like bio methanol that is discussed above).

For creating electricity, we have multiple methods:

- **Internal combustion engines:** these engines can be directly run on syngas with minimal modifications. [55]

Figure 44. Internal combustion engine for syngas. [56]

- **Gas turbines:** the syngas is compressed and injected into the turbine where it gets burned after mixing with air creating enough power to turn the gas turbine that is connected to a generator. [57]

- **Solid oxide fuel cell:** using this fuel cell will convert CO into CO_2 and H_2 into H_2O using an anode, cathode and electrolyte infused with air. The end product is electricity together with the carbon dioxide and water. [58]

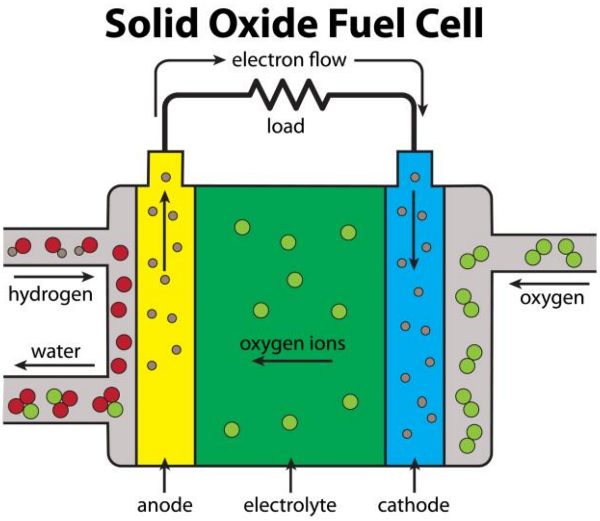


Figure 45. Solid Oxide fuel cell. [59]

For generating hydrogen out of the syngas, the gas has to go through a purification process to clean out all the imperfections so that only the hydrogen remains. This method is obviously a good solution with syngas that is rich in hydrogen.

Cost analysis:

In this kind of project it is important to look at both the performance of your system but also the cost. The two most useful costs are CAPEX (Cost of Construction) and OPEX (Cost of Operation). We will go over these costs for every reactor to see which technology is the cheaper option and which is the more expensive option.

Table 16 Cost expectation from different gasification reactors. [60] [61]

Reactor type	CAPEX range	OPEX (€/kWh)	Notes
Fixed bed	1965–5235 €/kW	0.034 €/kWh	Suited for small-scale; simpler, but lower throughput
Fluidized bed	1965–5235 €/kW	0.048 €/kWh	Medium to large scale; higher tar content management costs
Entrained flow	280–1100 €/kW (scale-dependent)	0.042-0.074 €/kWh	Cost drops with scale; includes costs for torrefaction, ASU, grinding

We can conclude several things out of this table. First, the lowest CAPEX is whit the entrained flow reactor, while both fixed bed and fluidized bed reactor's have the highest CAPEX. With the OPEX, we can see fixed bed reactors are the cheapest. The entrained flow reactor would be a good choice if we want a really large scale reactor so that we keep our cost of operation as low as possible.

After lots of searching for costs of bio methanol synthesis process, we couldn't really find costs specific for methanol made from biomass. We found a study about the cost of methanol synthesis using coal but that is not really applicable to our study.

10.2.4 Advantages/Disadvantages

[4] [62] [63] [64] [65]

Advantages

1. **Flexibility of feedstocks**

   Gasification can handle lots of different feedstocks like: coal, wood, agricultural waste, industrial waste and even municipal solid waste. This is really useful because for bio methanol production, you can use biomass like potato waste without problems. That makes the whole process more versatile.

2. **Potential for clean energy**

   The syngas you get from gasification is cleaner than regular fossil fuels. When used in engines or turbines, it produces fewer pollutants. Plus, for making bio methanol, the syngas can be converted into methanol, which can replace fossil methanol and help reduce petroleum use. So it's a cleaner, renewable fuel option.

3. **Byproducts can be used or treated**

   The leftover ash or slag from gasification can sometimes be used in construction materials, which means less waste is formed. Also, the process generates waste heat, this can be reused for things like combined heat and power (CHP), which improves overall energy efficiency.

Disadvantages

1. **High costs**

   Building a gasification plant that also produces methanol costs a lot of money upfront. Running the plant isn't cheap either because the system is complex. You need extra steps to clean the syngas really well before it can be turned into methanol, and that adds to the cost.

2. **Complex process**

   Gasification itself is tricky because it needs precise control over temperature and oxygen. After that, for methanol synthesis, the syngas has to have the right ratio of hydrogen to carbon monoxide, and all the impurities like tar and sulphur must be removed. This makes the whole setup quite complicated.

3. **Environmental concerns**

   Even though gasification is cleaner than burning fossil fuels, it still produces CO_2 and other emissions. Tar can be a problem in the syngas and needs extra cleaning. Also, if the ash or slag isn't disposed of properly, it can cause environmental damage.

4. **Energy use**

   Gasification requires very high temperatures—around 1000°C—which means it uses a lot of energy. Methanol synthesis also needs controlled conditions that consume energy. So, even though you can recover some heat, the process still uses a lot of power overall.

5. **Water use**

   The gasification process, especially if steam is used, needs a lot of water. This is also true for some steps in methanol production like cooling and cleaning. This can be a problem in places where water is scarce.

10.2.5 Companies

Xylowatt: Belgium [66]

This company mainly focusses on dry biomass so before this technology can be used with potatoes, we have to make sure that the moisture content is low enough. The moisture content of a potato is around 70-80% so maybe this isn't the best solution for our case. The system that Xylowatt uses can divert 650 kg of dry mass into 2MW of syngas in around 1 hour so that is around 1300Nm³ of syngas per hour. This company mainly focusses on the production of syngas, so another system is needed for bio methanol production.

Modular plant solutions [67]

This company specializes in creating methanol out of syngas on a small scale. The quantity of the syngas their plant could handle is 10200 mmBtu/day, which is the equivalent of 33600 Nm³ of syngas. The 2MW/h that the installation produces is equal to around 1300 Nm³/h. The output that the plant has is 300 metric tons per day. So this installation could be combined with the gasifier from Xylowatt.

Enerkem: Project El Morell Spain [68]

This project from Enerkem is the full package of using organic material to create syngas and after this convert it into bio methanol. The plant in El Morell can convert 400000 tons of biowaste into 240000 tons of methanol per year.

Topsoe [69]

This company focuses mainly on production from bio methanol with the specific use of syngas made with biomass as a feedstock. They have a small-scale system that can produce approximately 100 metric tons of methanol a day using around 100000 Nm³ of syngas per day.

10.3 Transesterification – biodiesel

10.3.1 Pretreatments

a. Enzymatic or Chemical Hydrolysis

The Objective is to break down complex carbohydrates in potato waste to release fermentable sugars, which can then be converted into lipids by microorganisms. Enzymatic hydrolysis uses enzymes such as amylase, cellulase, and pectinase to break down starch and fibre in potato peels. Chemical hydrolysis, on the other hand, uses acids like sulfuric acid to convert polysaccharides into simple sugars. These processes increase the release of sugars from potato waste, which supports microbial lipid production. They also improve the efficiency of biogas generation and offer potential for biodiesel feedstock. [70] [71]

b. Solvent Extraction

The objective is to directly extract lipids from potato waste using organic solvents. The process involves drying and grinding the potato waste to increase surface area, then applying solvents such as hexane, ethanol, or methanol to dissolve the lipids. The solvent-lipid mixture is then separated, and lipids are recovered after the solvent is evaporated. This method allows lipid extraction, although the yield is usually low because potato peels contain little fat. However, it may also help recover valuable compounds like phenolics along with the lipids. [72] [73]

c. Mechanical Pressing

The objective is to physically extract liquids, including possible lipids, from potato waste using pressure. This involves applying mechanical force with equipment like screw presses to remove water from potato peels. The liquid that comes out may contain dissolved or emulsified lipids. However, this method has limited success in extracting large amounts of lipids because potato waste has low oil content. It is mainly useful for reducing moisture rather than recovering lipids. [74]

Finally, you will find a summary table of what may or may not be a solution:

Table 17: Comparison of pretreatments

Method	Process	Yield	Outcomes
Enzymatic / Chemical Hydrolysis (followed by microbial lipid production)	Use of enzymes (amylase, cellulase) or acids (H_2SO_4) to break down starch into sugars for microbial lipid production	**2.6 - 11.2 g/L** lipid from hydrolysate depending on organism and conditions	Viable lipid production for transesterification; lipids mainly C16–C18
Solvent Extraction	Use of hexane, ethanol, or methanol to dissolve lipids from dried potato waste	**Low, often <1% (w/w)** lipid from dry mass	Low yield due to minimal native oil in peels; used more for phenolic recovery
Mechanical Pressing	Physical pressure to express liquids from peels; sometimes with steam	**Negligible oil yield** (focus is on moisture removal); ~82% moisture left	Not effective for lipid extraction; some juice recovery possible

Among the tested methods for lipid recovery from potato waste, only hydrolysis followed by microbial fermentation shows real potential. Solvent extraction and mechanical pressing are limited by the naturally low lipid content in potato peels, resulting in poor yields. These methods may offer side benefits like phenolic or juice recovery, but they are not suitable for scalable lipid production.

In contrast, hydrolysis, whether enzymatic or chemical, can convert the high starch content in potato waste into fermentable sugars. These sugars serve as feedstock for oleaginous microorganisms, which can accumulate lipids within their cells. Several studies using this approach have reported lipid yields ranging from 2.6 to 12 g/L, depending on conditions and microbial strains. The lipids produced are mostly composed of C16–C18 fatty acids, suitable for biodiesel conversion via transesterification.

Therefore, hydrolysis combined with microbial lipid production stands out as the most effective route. The second table summarizes key experimental setups that support this conclusion.

Table 18: Focus on microbial lipid production

Pre-treatment	Reactor/System	Fermentation Time	Lipid Yield	Fatty Acid Profile
Thermal acid deproteination (for potato wastewater) + added sugars (glucose, glycerol) [75]	Shake flasks (150 mL), 50 mL medium, 28°C, 160 rpm	72 hours (3 days)	Up to **11–12 g/L** (40% lipid in biomass)	Mainly C16:0, C18:0, C18:1, C18:2
Dilute acid hydrolysis (0.5% H_2SO_4, 100–160°C, 90 min) [76]	5 L acid hydrolyzer + yeast fermentation	~6 days	**2.6 g/L lipids** from *Rhodotorula mucilaginosa*	Not specified; typical profile = C16–C18

10.3.2 General process

The aim of this section is to determine whether transesterification technology can be used to produce biofuels from potato waste. Let's start by defining the process. Transesterification is a chemical reaction used mainly in the production of biofuels, in particular biodiesel. It involves transforming triglycerides, molecules found in fats and oils, into methyl esters (biodiesel) and glycerol, by reaction with an alcohol, generally methanol or ethanol, in the presence of a catalyst.

Why might this technology be of interest to us?

It is a process that is already widely used to recover oily waste, such as used cooking oil, and its products are well established on the market. What's more, this reaction is based on a relatively simple and adaptable method. It is therefore worth investigating whether potato waste could also be recovered in this way.

With this in mind, if we want to adapt the process to our raw material, here's what the overall transformation diagram would look like:

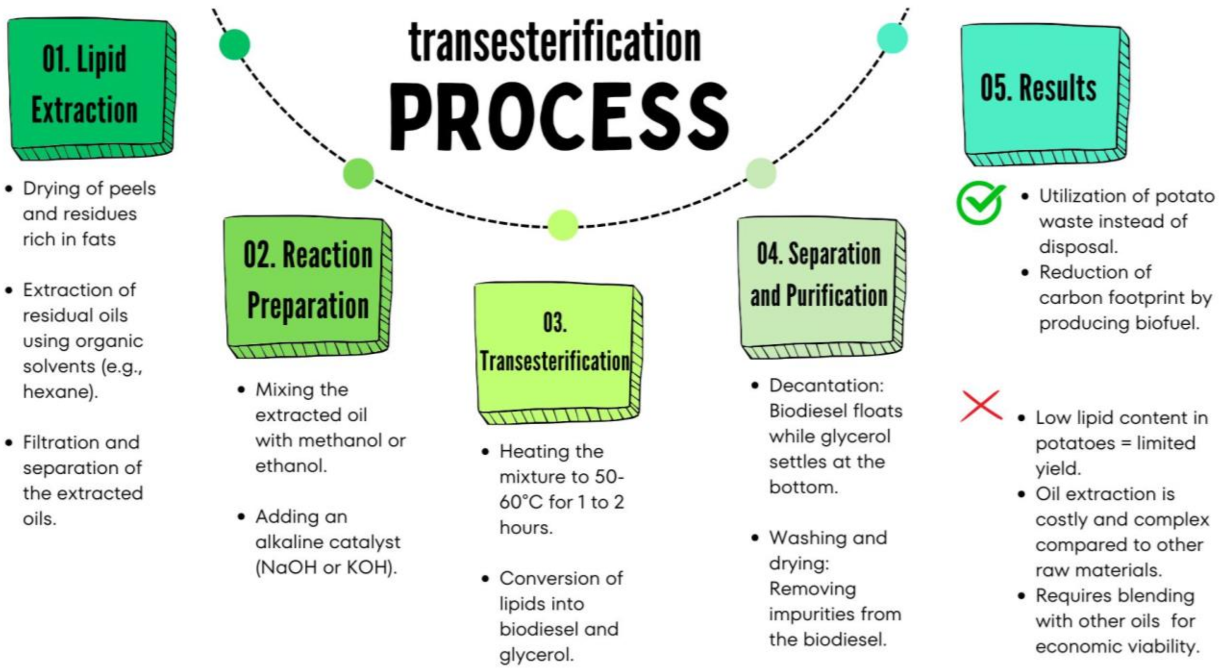


Figure 46. Transesterification process.

We can see that this waste cannot be used directly because it is naturally low in lipids. However, it is now interesting to see whether this waste can be used indirectly as a resource to produce compounds that can be used in this reaction. This is what we are going to look at through various pre-treatments.

10.3.3 Alternative

As well as trying to extract lipids from waste, another alternative is also being developed. This involves using potato waste not as a raw material but as a catalyst in the process. Studies show the possibility of forming 'green' heterogeneous catalysts, which would make the creation of biodiesel even more eco-responsible. These catalysts can be produced by thermally treating the ash or residue left after processing potato waste, creating solid bases suitable for transesterification. Using waste-derived catalysts not only reduces the need for conventional chemical catalysts but also adds value to agri-food residues. This approach supports a circular economy model by converting a waste product into a functional input in biodiesel production. [77] [78]

The process consists of two principal steps [79] :

CONVERSION OF POTATO WASTE TO ASH

10 kg of potato waste → sun-dried for 72 hours, reducing the mass to 2 kg → 2 hours of burning at 600°C → 16% of the dried potato waste

KOH EXTRACTION FROM POTATO WASTE ASH

20 g of calcined potato waste ash → mixed with distilled water → heated and stirred continuously at 60°C for 2h → filtered and dried by heating → 34% potassium hydroxide

figure 47: Extraction of green KOH from potato waste [79]

It is therefore worth carrying out a predictive analysis of the viability and feasibility of this alternative. [80] [81] [82] [83]

Analysis:

Environmental Sustainability:

GHG Reduction: Replacing synthetic KOH with waste-derived KOH reduces emissions associated with industrial catalyst production.

Energy Efficiency: Potato-waste-based catalyst improves biodiesel reaction efficiency, but ash extraction and processing still require energy.

Water Impact: KOH leaching from ash uses water and generates greywater; low volumes, but no data on water reuse.

Waste Reduction: Very good; turns a bulky agricultural-waste into a functional product. But only a fraction of total waste mass becomes catalyst.

Carbon Footprint: Lower than industrial KOH, but not carbon-neutral; combustion of waste produces CO_2, albeit offset somewhat by avoided waste.

Economic Viability:

Capital Investment: Low-tech setup, but still needs combustion, filtration, and drying systems. Not plug-and-play.

Operating Costs: Cheap inputs, but fuel/electricity required for ash processing; labour and quality control costs not negligible.

Revenue Streams: You're only selling catalyst. No fuel, no direct energy product = limited market and low profit margins unless scaled.

Payback Period: Hard to estimate. Likely long payback unless integrated with existing biodiesel operations.

Market Readiness: Very low. Biodiesel producers are not widely using waste-derived KOH; may face scepticism and quality assurance issues.

Scalability: Theoretically scalable, but economic returns may not justify upscaling unless matched with oil feedstock availability.

Technical Feasibility:

Technology Readiness Level (TRL): TRL 5-6; lab-scale only. No evidence of industrial adoption yet.

Process Complexity: Not highly complex, but needs consistency in ash composition, leaching process, drying, etc.

Conversion Efficiency (in biodiesel): When paired with oil, catalyst works well (up to 92.9% yield); but we don't have oil. This is theoretical in our case.

Adaptability: Limited; this is only valuable in biodiesel contexts. Without an oil source nearby, there's little use.

Infrastructure Needs: Requires custom setup for waste burning, ash processing, storage, QC lab, etc.

Social Considerations:

Job Creation: Some jobs in catalyst processing but low compared to energy-producing projects.

Rural Development: Potential, but only if integrated into larger regional biofuel systems.

Energy Security: Indirect at best; we are not producing any fuel, just a supporting component.

Public Acceptance: Likely positive if framed as circular economy but limited public excitement around industrial ash processing.

Regulatory Compliance: Unclear; no established quality standards for "bio-KOH" catalysts; would require validation.

10.3.4 Output

Biodiesel is a renewable biofuel capable of replacing conventional diesel. It can be used in diesel engines with little or no modification and is often blended with regular diesel (B20 = 20% biodiesel, 80% petroleum diesel). Currently, diesel remains the primary fuel for various types of vehicles; however, as a fossil hydrocarbon, its production, transportation, and combustion contribute significantly to greenhouse gas emissions. This has intensified the global search for viable alternatives, with biodiesel emerging as a promising solution.

Biodiesel is primarily derived from vegetable oils, including used cooking oils, or from processed animal fats. It can be directly utilized in conventional diesel engines without significant modifications. The most widely adopted production method is transesterification which exhibits similar properties to conventional diesel fuel.

An alternative type of biodiesel, hydrotreated vegetable oil (HVO), is produced using hydro processing, a method like petroleum refining. Unlike FAME, which retains oxygen molecules, HVO is fully hydrogenated, removing oxygen and producing a paraffinic fuel with superior combustion characteristics, higher cetane number, better stability, and improved cold-weather performance. HVO can be used as a direct drop-in fuel (HVO100) without blending, whereas FAME is typically blended with petroleum diesel due to its different physical and chemical properties.

The production processes for biodiesel and conventional diesel also differ significantly. Petroleum diesel is derived from crude oil through fractional distillation, where hydrocarbons are separated by boiling point, followed by further refining and treatments such as hydrodesulfurization. In contrast, biodiesel (FAME) production involves esterification or transesterification, which converts triglycerides into esters, resulting in a product with different viscosity, density, and combustion characteristics compared to diesel. Additionally, FAME contains oxygen, making it more prone to oxidation and microbial contamination in storage, whereas petroleum diesel and HVO are more stable. [84]

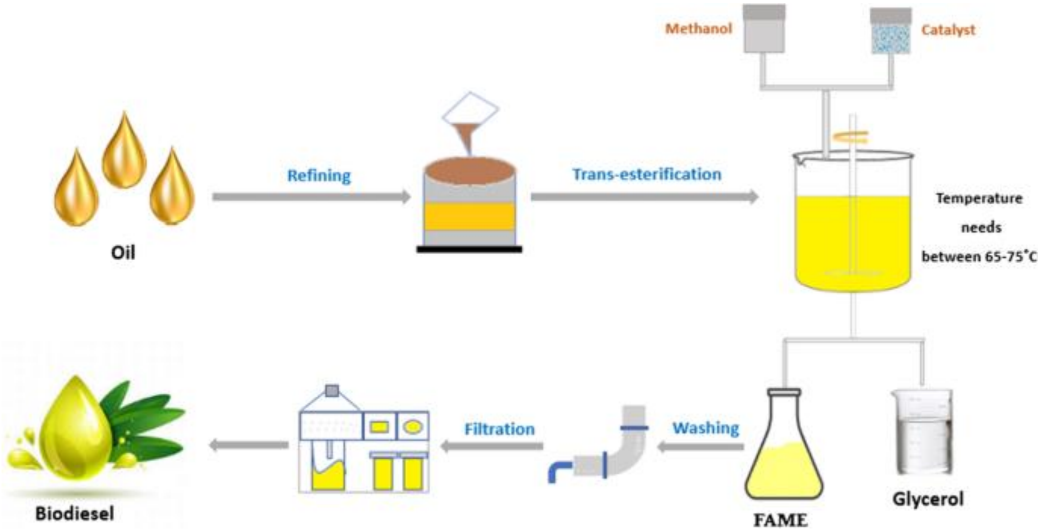


figure 48: Biodiesel creation process. [84]

Cost analysis:

In this cost study we will concentrate on the production of heterogeneous catalyst. The main stages are drying, grinding and calcination. These stages are the costliest in terms of the equipment required, but other costs are also involved, such as labour and consumables.

The cost of the equipment can be summarised in the table below:

Table 19: Equipment cost to produce green catalysts

Equipment	Cost	Service life
Calcination furnace (800°C)	5000 – 10000 €	5 – 7 years
Electric dryer	1500 – 3000 €	5 years
Laboratory grinder	1000 – 2000 €	5 years
Scales, sieves, accessories	Around 1000 €	5 years

Added to this is the cost of energy, estimated at €2 per kg of potato waste processed. Assuming 100 kg/day of processed waste, this would mean around 5 to 10 kg of catalyser at a daily cost of €10 to €15. Given that the commercial equivalent can range from €50 to €100, this would represent a saving of €40 to €80.

Of course, this calculation is based on estimates and in an ideal model. The real cost of electricity, the scale of production, the efficiency of the machines and their reliability would have to be considered.

10.3.5 Advantages/Disadvantages

Advantages:

- Reduction in CO_2 Emissions: Biodiesel can reduce carbon dioxide emissions by 50–60% compared to fossil diesel, as observed in certain European countries.
- Biodegradability and Lower Toxicity: Unlike petroleum-based diesel, biodiesel is biodegradable and exhibits lower toxicity, thereby minimizing environmental risks in the event of spills.
- Economic and Employment Benefits: The biodiesel industry contributes to job creation, particularly in agriculture (for oilseed crop cultivation) and in processing and refining sectors.

Disadvantages:

- Impact on Land Use and Food Security: Large-scale biodiesel production often relies on dedicated crop cultivation, which may compete with food production, potentially leading to deforestation and loss of biodiversity.
- Emission of Nitrogen Oxides (NOx): Biodiesel combustion generates higher NOx emissions, a key air pollutant with adverse effects on human health.
- Economic Constraints: Biodiesel production remains more expensive than fossil diesel, largely due to the necessity for specialized processing facilities, although existing refineries can be adapted for biodiesel production with relative ease.

10.3.6 Companies

French company : Avril

The Avril Group has been a major player in biodiesel production in France since the 1990s, thanks to its two flagship products: Diester and Oleo100.

Diester®:

- Launched in the early 1990s - this biodiesel is mainly made from rapeseed oil and is one of the first biodiesels produced in France
- Type: FAME (Fatty Acid Methyl Ester)
- Today, 7% of biodiesel is blended into diesel fuel for all diesel-powered vehicles in France, making it the market leader for biodiesel in France

Oleo100 :

- B100-type biodiesel
- It can be used as a total replacement for conventional diesel without engine modifications
- Entirely plant-based, renewable and traceable fuel, made from French rapeseed, it adds value to the rapeseed industry in France, contributing to a local and sustainable economy

Avril has been a pioneer in biodiesel with Diester® since the 1990s and is now the leader in B100 with Oleo100.

American company : Renewable Energy Group

Renewable Energy Group (REG) is an American company specializing in the production of biofuels, mainly biodiesel.

In 2022, Chevron acquired REG for $3.15 billion, strengthening its presence in the renewable energy sector. Therefore, in 2023, REG produced more than 1 billion liters of biodiesel, helping to reduce emissions by 3.8 million tons of carbon, demonstrating the positive environmental impact of its activities.

REG uses non-edible raw materials such as:

- used oils: working with partners such as Sheetz and Restaurant Technologies to recycle used cooking oil, creating a circular economy
- non-edible biomass: in partnership with ExxonMobil and Clariant, the company is exploring the use of cellulosic sugars from agricultural residues to diversify raw material sources

So, the company mainly produces FAME biodiesel, in the form of B100, using innovative technologies that make use of inedible raw materials, thereby limiting waste and helping to reduce carbon emissions.

Irish company: Green Biofuels Ireland

Major player in biodiesel production in Ireland, and the country's largest commercial-scale producer, the company specializes in converting biodegradable waste into high-quality FAME B100 biodiesel.

Like the two companies mentioned above, Green Biofuels Ireland (GBI) collects used oils from various sectors (catering, food industry, etc.) and recycles them into biodiesel. It also obtains its raw materials from the meat industry, by recovering rendered animal fats.

The whole process recycles unused waste, avoiding waste and contributing thereby to a circular and sustainable economy.

Finnish company : Neste Oyj

Finally, last but not least, the finish one: Neste.

World leader in the production of biodiesel and specializing in renewable energies and petroleum products, it is 50.1% owned by the Finnish state.

History of Neste:

- 1948: Neste is founded as a state-owned oil company in Finland, with the task of supplying refined fuels.
- 1980: Start of investment in research and development of renewable energy solutions.
- 2007: Launch of NEXBTL technology, enabling the production of renewable diesel from various raw materials (vegetable oils, animal fats, etc.).
- 2015: Change of name from Neste Oil to Neste, marking an increased focus on renewable energies.

Neste has renewable diesel refineries in Singapore (operational since 2010) and Rotterdam. In 2023, it created a joint venture with Marathon Petroleum, called Martinez Renewables, in California, strengthening its presence in the global market.

For its biodiesel, the company uses the NEXBTL technology. This makes it possible to produce high-quality renewable HVO diesel from renewable raw materials such as vegetable oils and animal fats. This diesel is chemically identical to fossil diesel, so it can be used directly in existing diesel engines, without any modifications.

Neste has transformed itself from a traditional oil company into a world leader in renewable fuels, with a capacity to reduce CO2 emissions by 90%.

Conclusion

Biodiesel production is expanding worldwide, driven by the growing demand for renewable energy and more sustainable fuel alternatives. As a biofuel, it has solid foundations, offering significant environmental benefits despite certain flaws in its manufacturing process, such as high production costs and emissions of nitrogen oxides.
However, while biodiesel is a viable solution, the specific project of producing it from potato waste appears to be impractical given the limitations we face in securing a sufficient and consistent supply of raw materials. The challenges related to resource availability make large-scale implementation difficult, reducing the feasibility of this approach within our project.

10.4 Anaerobic digestion - biogas

Anaerobic digestion is a process wherein microorganisms break down organic material in the absence of oxygen such as food waste. This results in the creation of biogas, which mainly consists of carbon dioxide (CO_2), methane (CH_4) and a residue rich in nutrients which can be used as a fertilizer [85].

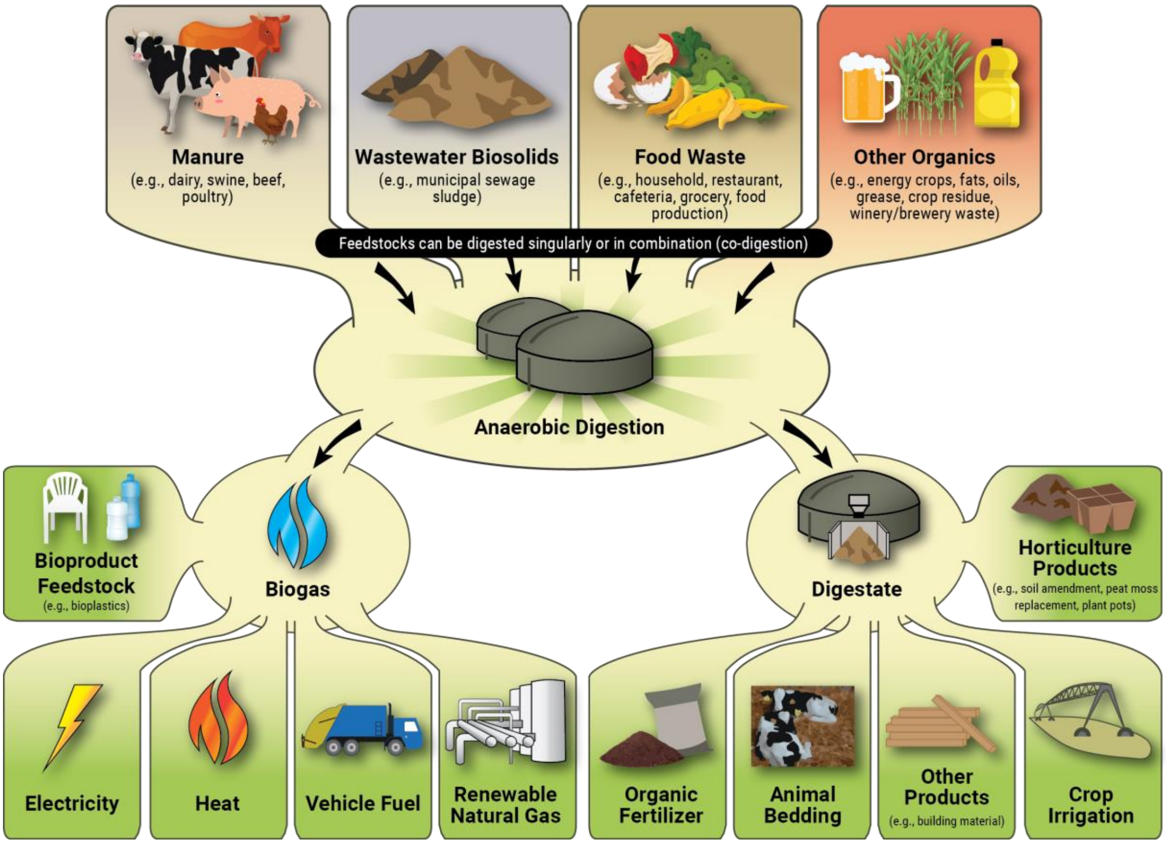


Figure 49. Anaerobe digestion process and applications. [85]

10.4.1 Pretreatments

To maximize the output from the potato waste, it needs pre-treatment. This is done to increase the surface area of the potato waste, which causes the waste to be more exposed to the process. The pre-treatment can be done in multiple ways:

1. **Hollander beater**

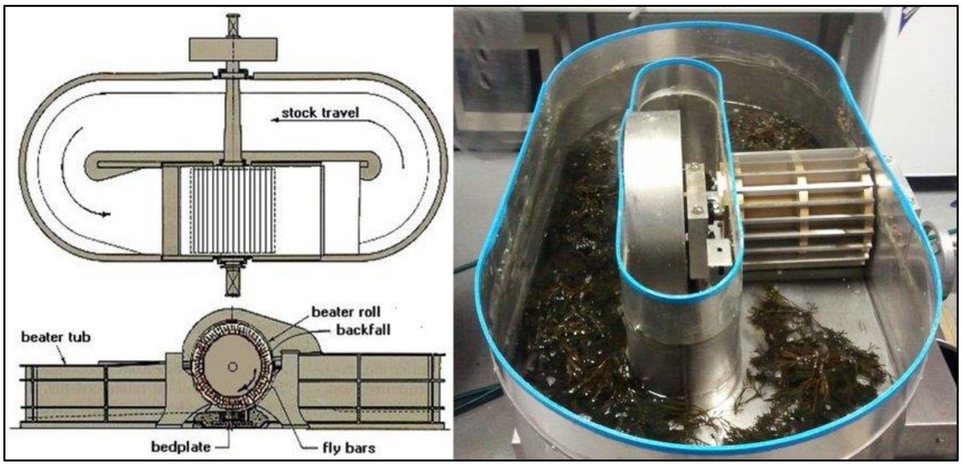


Figure 50 [135]

Visual of a Hollander beater. It breaks down fibrous structure of the waste by grinding and shearing, increasing the surface area and improving microbial accessibility.

2. **Steam pre-treatment**

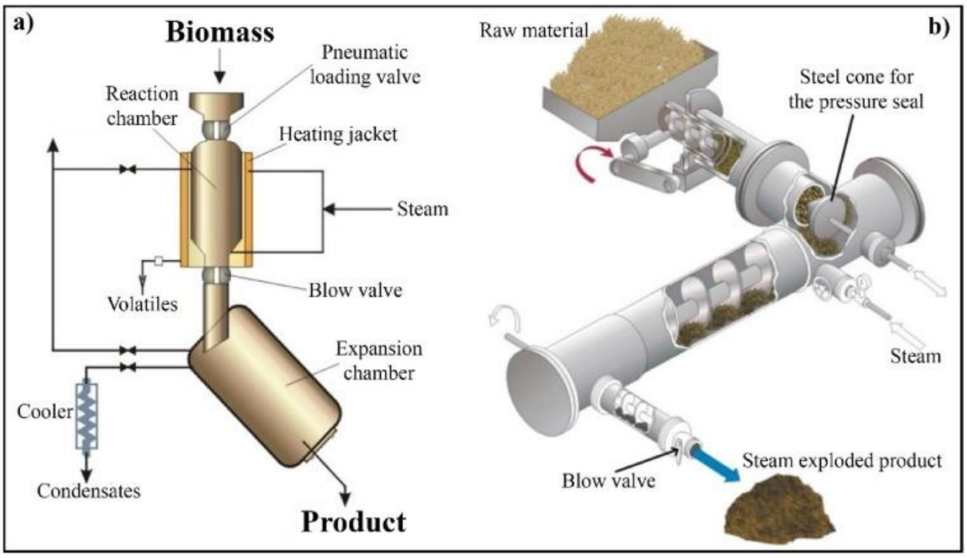


Figure 51 [86]

Steam pre-treatment involves exposing potato waste to high-temperature steam under pressure for a short period, followed by rapid depressurization. This process disrupts cell walls, gelatinizes starches, and solubilizes hemicellulose, making the organic matter more accessible to anaerobic microbes.

3. Organosolv pretreatment

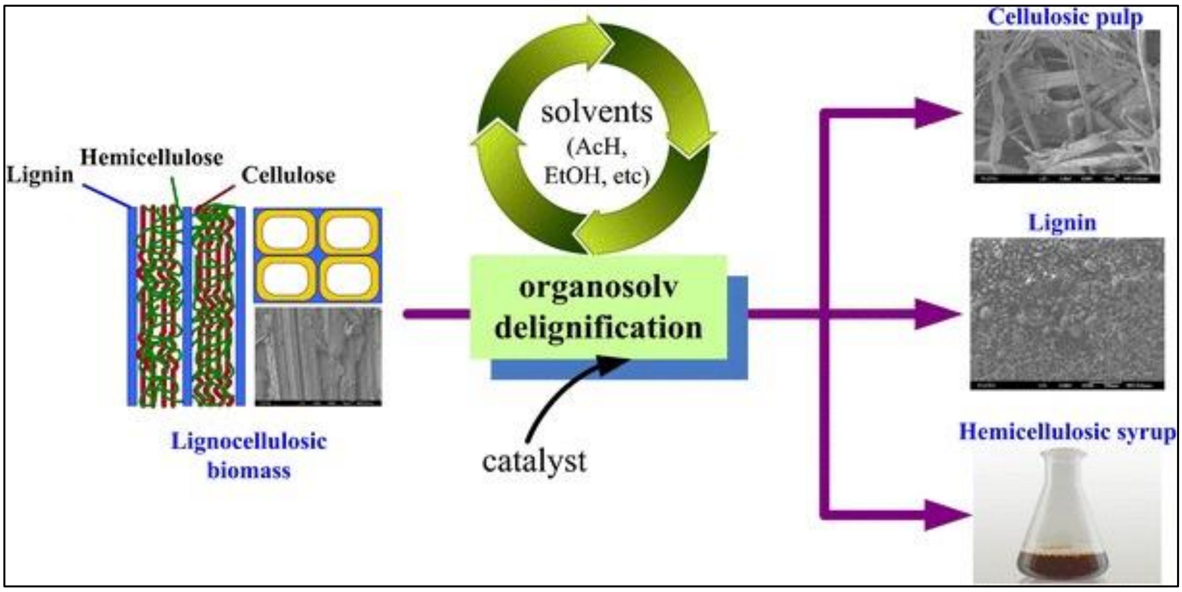


Figure 52 [87]

Organosolv pre-treatment uses organic solvents (such as ethanol or methanol) mixed with water, often under heat and pressure, to break down lignocellulosic components in potato waste. This process effectively separates lignin and hemicellulose, enhancing the digestibility of the remaining cellulose for anaerobic microbes.

Conclusion

For anaerobic digestion, multiple pre-treatments are possible. The Hollander beater is a good option for small-scale anaerobic digestion plants. Whilst the organosolv pre-treatment method is effective, it is still in its development stages and is not fully commercially available. Therefore, the Stream pre-treatment will be chosen to investigate further in the cost analysis among other things.

10.4.2 General process

The biochemical process consists of three stages [88]:

1. **Hydrolysis:**

Insoluble organic polymers such as cellulose, carbohydrates, fats and proteins are broken down and liquefied by enzymes produced by microorganisms. Lipids, proteins and carbohydrates are hydrolyzed to sugars which then decompose further to hydrogen, carbon dioxide, organic acids and ammonia. Proteins decompose to form carboxylic acids, ammonia and more carbon dioxide. In this process the concentration of gasses accounts for 20% hydrogen and 80% carbon dioxide.

2. **Acidogenesis:**

In the second phase are the organic acids created in the first phase converted by acetogenic bacteria into acetic acids. After this stage, carbon dioxide and hydrogen concentration begin to decrease.

3. **Methanogenesis:**

During the third stage, methane and carbon dioxide are produced from organic acids and acetic acids. Methane is partially produced by the added methanogenic bacteria. During this stage, the contents of the container are mixed to improve the surface contact of the different materials. The acidity levels in the container are also closely monitored since it greatly impacts the balanced growth of bacteria.

Purification process

During the process, not only methane is produced in the tank. CO_2, H_2S, water vapor and ammonia are also created. To capture the methane, a purification process is performed:

1. *Desulfurization*

Iron oxide filters, activated carbon or biological filters are used to remove the H_2S.

2. *Drying*

Cooling/condensation, adsorption or membranes are used to remove the water vapor.

3. *Carbon dioxide removal*

Water scrubbing, chemical absorption, pressure swing adsorption (PSA), membrane separation or cryogenic separation can be used to remove the CO_2 from the methane to improve the energy content

4. *Removal of trace compounds*

Activated carbon filters or advanced chemical scrubbers may be used to remove the last few trace compounds such as ammonia, siloxanes and volatile organic compounds (VOCs)

Reactors

There are two kinds of scale anaerobic digestion can be performed upon: low-rate anaerobic systems and high-rate anaerobic digestion systems. [89]

Low-rate anaerobic systems

- Septic tanks

A basic, passive system where solids settle, and digestion happens in a tank underground. It is used primarily for domestic wastewater treatment but can also be used for other forms of bio-waste. Septic tanks can typically handle an inflow range of 2 to 200 m^3 per day. [90]

- Anaerobic pond

A large, open, earthen basin that treats bio-waste through anaerobic processes. Sludge [91] accumulates over time which can later be used as nutrient rich digestate. Anaerobic ponds typically have a bio-gas production rate of 0.07 to 0.16 m^3 per day. [92]

- Covered anaerobic pond

Similar to an anaerobic pond but with a covered impermeable roof that collects biogas and reduces odors expelled by the process. Covered anaerobic ponds produce biogas in the same range as normal anaerobic ponds, ~0.07 to 0.16 m^3 per day. [92]

High-rate anaerobic systems

- Continuous stirred tank reactor (CSTRs)

A fully mixed tank where feedstock is added semi-continuously or continuously. Commonly used on the average farm, it usually produces 0,49 L of bio-methane per hour. [93]

- Anaerobic contact

Similar to the activated sludge process. In an anaerobic contact reactor, biomass is separated after digestion and returned to the reactor. On an industrial scale, typically 2,96 m^3 of bio-methane is produced per day. [91]

- Up-flow sludge blankets

Waste-fluid flows upward through a dense sludge bed where microorganisms digest organic materials. USP is commonly used in situations of high biomass retention and efficiency. It typically produces around 2,97 L methane per day. [94]

- Anaerobic membrane bioreactors

Anaerobic membrane bioreactors combine anaerobic digestion with membrane filtration to retain biomass and to separate the solids/fluids. The technology is new to the commercial market but has an average yield of 0,14 m^3. [95]

Analysis

Environmental Sustainability:

GHG Reduction: High, it reduces GHG emissions in the sense that it captures methane produced from waste. [96]

Energy Efficiency: 52.9% [97]

Water Impact: 0.31–1.09 m^3 sw_e/Mg waste [98]

Waste Reduction: anaerobic digestion offers a significant quantitative reduction in food waste, with the capacity to divert millions of tons annually from landfills in countries like the U.S., EU nations, and China. [99]

Carbon Footprint: 59.93–4,217.78 kg CO_2/ton waste [100]

Economic Viability:

Capital Investment: High (3-4 million USD)

Operating Costs: low- moderate (2 – 7% of the capital investment) [101]

Revenue Streams: Bio-methane with a rich nutrient digestate as a by-product

Payback Period: between 5 and 12 years [102]

Market Readiness: Commercially established

Scalability: according to a study: "A strong correlation was found between the three digester sizes, indicating the scalability of AD is tenable. However, some statistically significant differences in biogas production showed that there is a scaling effect that must be taken into account." [103]

Technical Feasibility:

TRL: 9 (commercial to fully commercial)

Process Complexity: Moderate

Conversion Efficiency: 79% [104]

Adaptability: Remarkable adaptability

Infrastructure: Requires specialized equipment

Social Considerations:

Job Creation: Moderate - Low

Rural Development: Good potential for agricultural integration

Energy Security: Contributes to gas fuel independence

Public Acceptance: Generally positive

Regulatory Compliance: Well-established frameworks

Conclusion

Based on the presented data, the optimal anaerobic digestion system depends on the purpose and the scale of the application. For small-scale, low-rate systems like covered anaerobic ponds and septic tanks offer a simple, low-maintenance solution. For medium to large-scale operations, continuous stirred tank reactors (CSTRs) provide a good balance of practicality and efficiency. On an industrial scale, anaerobic contact reactors yield the highest biogas output and are perfect for processing potato waste.

Temperatures

The two most conventional process temperature levels for anaerobic digestion determine the specific bacteria in the container [105].

- **Mesophilic digestion**
  Mesophilic digestion takes place around 30 – 38 °C. In this temperature range, mesophiles are the primary microorganisms present.

- **Thermophilic digestion**
  In thermophilic digestion ranges the temperature around 49 – 57 °C. In this temperature range, thermophiles are the primary microorganisms present.

10.4.3 Output

Output materials

During the process of anaerobic digestion, two main products are produced: Bio-methane and nutrient-rich digestate. The main focus of anaerobic digestion is to convert bio-waste into fuel, therefore the majority of the focus in anaerobic digestion is laid on the first product, bio-methane. The residue of the process is however very nutrient rich and can be used as a fertilizer in farming,

Energy yield

Anaerobic digestion produces 300 – 400 L methane per kilogram bio-waste. This amounts to an energy yield of 11 MJ/kg bio-waste.

Cost analysis:

In this cost analysis we will concentrate on the production of bio-methane through the use of one of the reactors (CSTRs) and a pre-treatment method (steam pre-treatment).

The two components are essential for:

- Enhancing the biodegradability and gas yield of the potato waste
- Maintaining a stable, continuous anaerobic process

The cost of the equipment can be summarized on the table below:

Table 20. Cost analysis. [106] [107]

Equipment	Cost
Steam pre-treatment	$2.13 – $2.68 million
Laboratory scale CSTR (1 - 100 liters)	$1.000 - $12.000
Pilot scale CSTR (100 – 1000 liters)	$3.000 - $26.000
Industrial scale CSTR (1000 – 2000 liters)	$5.000 – $56.500
Large scale reactors (20.000 – 1.000.000 liters)	$10.000 - $500.000

If chosen, a steam pre-treatment and a CSTR reactor ranging from small to large scale can have costs between 2.14 and 3.18 million USD or 1.9 to 2.8 million euros.

10.4.4 Advantages/Disadvantages

For potato waste recycling, there are some strengths and weaknesses present for anaerobic digestion:

<u>Advantages</u>

- **Nutrient rich digestate**
  One of the byproducts of anaerobic digestion besides the produced methane, is the nutrient rich digestate. This can be used as fertilizer for the farmlands of the potato fields close to the anaerobic digestion tanks.

- **High efficiency with potatoes**
  Potatoes, especially waste starch or spoiled ones, can be broken down into methane-rich biogas, which can be used for energy generation.

- **Odor control**
  The whole digestion process takes place in a closed tank, which makes sure no bad smelling odors escape. Making the plant minimal in smell pollution.

<u>Disadvantages</u>

- **Pretreatment needed**
  Because the process takes place in a static chamber, the larger waste parts are not being broken down in the middle. Because of this, pre-treatment such as grinding and processing of the potato-waste is needed for the bacteria and other factors to reach the middle of the potatoes.

- **Initial investment**
  Whilst anaerobic digestion is an efficient solution to potato waste, an anaerobic potato digestion plant can be of high value. This initial investment is often times a too large of a step for smaller companies, especially with the third disadvantage on this list; scalability.

- **Scalability**
  Power generation through anaerobic digestion is best suited for large-scale plants, rather than small scale ones. This is because larger plants have a higher return rate in biogas per amount of potato waste. [108]

10.4.5 Companies

With the use of anaerobic digestion, emission of greenhouse gases can be reduced in several ways [109]:

- Replacement of fossil fuels
- Reducing or eliminating the energy footprint of waste treatment plants
- Reducing methane emissions from landfills
- Displacing industrially produced chemical fertilizers
- Reducing vehicle movements
- Reducing electrical grid transportation losses
- Reducing the usage of LP gas for cooking

Anaerobic digestion is a productive method for treating solid organic waste. It reduces the total volume of the waste material and decreases the damaging methane emissions. It is widely used regarding environmental regulations, where the process can handle municipal waste on its own in specialized plants. Local anaerobic digestion facilities lower the amount of transport emissions normally produced with conventional gas production.

An example of an application on anaerobic digestion is the potato product producer Cavendish farms [110]. This north American company completed its first construction on a anaerobic digestion facility to generate biogas from potato waste. The waste includes potato plant residues, starch, spent frying oil and aerobic sludge from the existing wastewater treatment plant. The facility handles production rates of 120 thousand tons per year of feedstock, or an average input of 360 tons per day.

The facility began development in 2006 after two years of project evaluation. The wastewater treatment plant was already operating for more than 10 years and had already been using anaerobic sludge to produce soil conditioner.

The company now uses the generated biogas to facilitate the power for the boilers in its two co-located processing plants. The leftover digestate material is used as fertilizer over fields instead of the use of potato waste/sludge, reducing the smell.

10.5 Fermentation - bioethanol

Introduction to the process:

The focus of this introduction is purely to inform the reader with background information, and terms of the process which are the foundation of this process. After this introduction will follow a detailed overview and explanation of the terms and every attribute that is needed to successfully produce bioethanol. After this, the same order will be followed as mentioned in the introduction of **Technologies p. 42**.

Bioethanol is the result of a process called fermentation. The end produce is alcohol. This can be produced by the fermentation of starch. Another possibility is fermenting the lignocellulosic substrates via microorganisms. Recyclable carbon dioxide, heat and water are to be released in both processes. The process behind bioethanol, exists of 4 main stages:

1: **Pretreatment** of cellulose substrate to produce hemicellulose or lignin.

2: **Hydrolysis** of cellulose to obtain fermentable sugars.

3: **Fermentation** of sugar into ethanol by the biomass.

4: **Distillation** and purification of ethanol.

It is important to know that not all of these 4 stages are always necessary. For first – generation bioethanol (see next page), which is made of starch biomass and kernels. There is only the need for hydrolysis, fermentation and distillation and in the case of sugary biomass. There is only the need for fermentation and distillation. The most complex process, where alcohol is produced from cellulose, all the main stages have to take place.

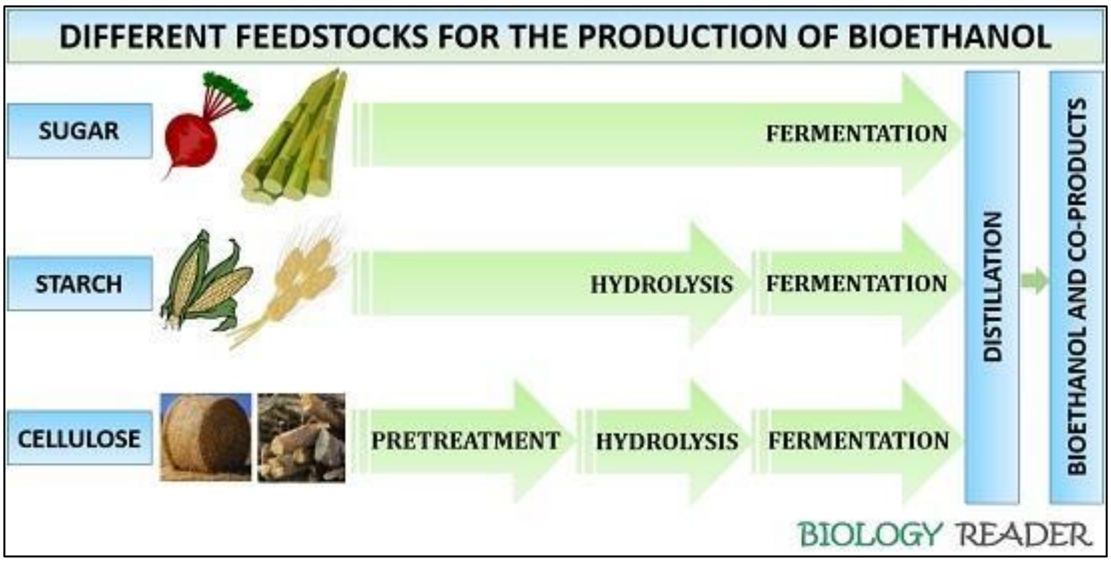


Figure 53. The difference in processes for different feedstocks. [111]

Bioethanol from potato waste

Our focus is of course potato waste, which falls into the category of starchy crops biomass. To be more specific in the category of the first-generation bioethanol. This generation makes use of kernels and starchy crops biomass like sugar-beet, sugarcane, wheat, corn etc. The production process requires more land area for the cultivation of crops, due to which the capital cost in the first generation is quite high. In our case, the potato waste is required for free. The bioethanol produced from such feedstocks contains a high sugar concentration compared to the other feedstocks.

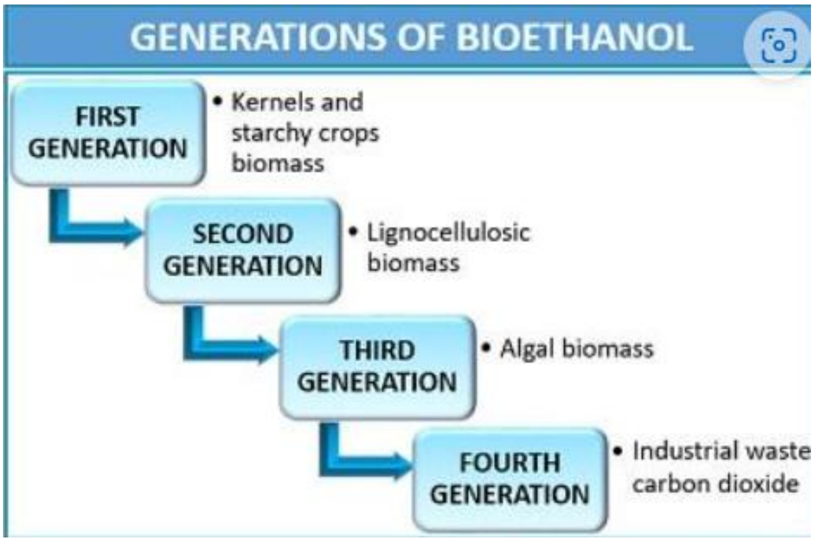


Figure 54. The different generations of bioethanol. [111]

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10.5.1 Pretreatments

The aim of pretreatment is to lessen the unwanted mass in the waste, hereby we mean the mass that can be destructive to the process or the equipment. It also (more importantly) makes the biomass more accessible and suitable for microbial or enzymatic action. Those key points can be broken down into the following points:

1. **Break down complex structures**: such as lignocellulosic biomass, to release fermentable sugars.
2. **Increase surface area**: by reducing particle size and altering structure for better enzyme or microbial access.
3. **Remove inhibitors**: like lignin, fats, or heavy metals that can interfere with microbial activity.
4. **Improve homogeneity**: making the substrate more consistent for controlled fermentation.
5. **Enhance biodegradability**: accelerating the conversion process and increasing the final product yield (e.g., ethanol, biogas, organic acids).

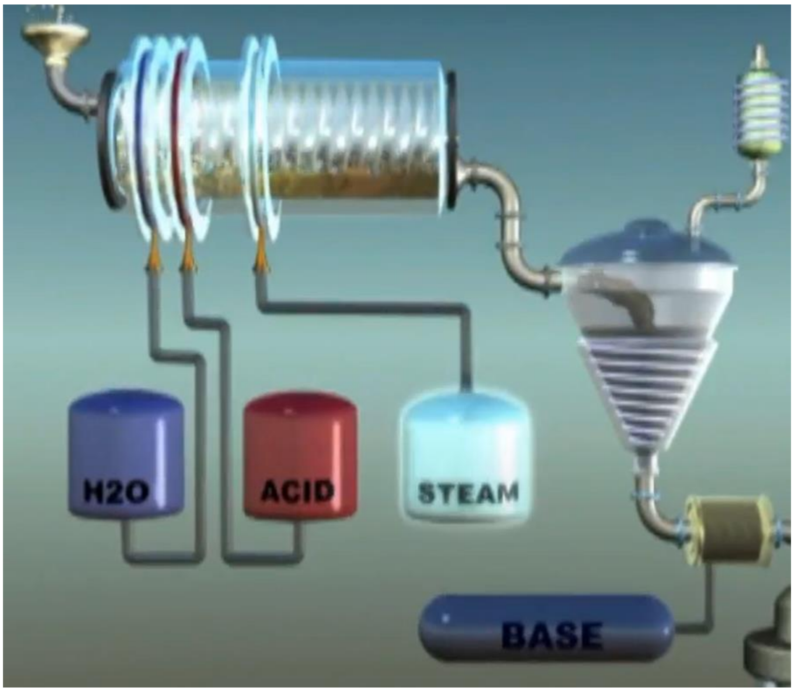

Figure 55. Visual of the first part of the pretreatment of the potato waste.

As seen in the figure the mass is first to be pretreated by steam and in some cases acid. This must be done so that the biomass is broken down into cellulose, heavy cellulose and lignin. Enzymes cannot operate in high acidic conditions thus follows the base which controls the acidic conditions. After this the enzymes can be added to the mixture (second part of pretreatment), thus performing hydrolysis. This process breaks down the cellulose chains into glucose and the hemicellulose chains into xylose. Glucose and xylose are sugars that can be most readily fermented into ethanol.

After this part two of the pretreatment will start, because off the wide usage of fermentation. There are a lot of studies to be found on which method is the best. Thus, the next information will consist out of the pretreatments found in said studies, the most effective and the most promising one for our application. The information will be shown in form of a table to give an overview, this table has been found in the following paper [112]. Followed by research which undoubtedly shows us the most promising pretreatment.

Table 21 Different pretreatments for fermentation.

Pretreatment Type	**Description**	**Advantages**	**Disadvantages**
Physical	Mechanical processes (e.g., milling, grinding) to reduce biomass particle size	Simple and increases surface area for further treatment	High energy requirement; doesn't break down lignin effectively
Chemical	Uses acids or alkalis to break down biomass	Effective delignification; widely studied	Can create toxic by-products; corrosive; higher utility and disposal costs
Physicochemical	Combination of heat/pressure and chemicals (e.g., steam explosion)	Disrupts structure and increases accessibility	Equipment-intensive; may still form inhibitors
Biological	Uses microorganisms or enzymes to degrade lignin and hemicellulose	Environmentally friendly; low energy requirement	Very slow; difficult to scale
Enzymatic Hydrolysis	Uses enzymes (cellulase, xylanase) to convert cellulose/hemicellulose to sugars	Mild conditions (40–50°C, pH 4–5); low toxicity; no inhibitors; energy-efficient	Substrate-specific enzymes; relatively slow; enzyme cost may be high

From this information we can conclude that enzymatic hydrolysis is the most promising pretreatment, in case of looking at the output (so not economically based). Compared to traditional acid hydrolysis, enzymatic hydrolysis needs less energy and milder operational conditions (approximately under the temperature of **40–50°C** and pH of **4–5**). The pH / acidic degree is controlled by the base (also part of the pretreatment). Hence, the advantages of enzymatic hydrolysis over acid saccharification include low toxicity, low deterioration and corrosion. Some other advantages are: low utility cost, no inhibitory by-product, and no environmental damage. However, enzymatic hydrolysis requires being carried out by substrate-specific enzymes, namely, the bonds of cellulose and hemicellulose are cleaved by cellulase and hemicellulase enzymes, respectively. Moreover, the cost of cellulase production in the industry is high due to the substantial cellulose loss, high energy consumption, and long fermentation time when it is prepared by microorganism fermentation. [113]

10.5.2 General process

Fermentation is a biological process in which microorganisms such as bacteria, yeast, or fungi convert organic substrates (typically sugars or carbohydrates) into simpler compounds, usually under anaerobic (oxygen-free) conditions. The most common fermentation products include: ethanol, lactic acid, hydrogen gas and carbon dioxide, depending on the type of microorganism and substrate used. [114]

The general process (fermentation) comes right after the enzymatic hydrolysis has found place. We have been researching fermentation based on yeast. A key consideration was the selection of an appropriate yeast strain for the best outcome in our project. This wasn't an easy step for us, given our backgrounds. None of us are specialised in the biochemical processes. Nevertheless, different studies gave us more and more insights into the use of yeasts. The next study shows us the different outputs of the types of yeasts. It also shows which studies researched which types of yeast, thus is the next table to be considered as a summary.

As to be seen on the next page, cerevisiae also called baker's yeast is the most promising and trustworthy yeast. This can be seen under the concentration of ethanol produced. The table also shows the importance of a controlled environment in which among others the Ph balance is important.

Cerevisiae ferments glucose and other sugars anaerobically: $C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$
That is: glucose → ethanol + carbon Dioxide. [115]

Table 22. *The difference in processes for different types of yeast. [116]*

Strain-species	Temperature (°C)	pH value	Carbon source and concentration (g/l)	Nitrogen source and concentration (g/l)	Incubation time (h)	Concentration of ethanol produced (g/l)	References
27817-*Saccharomyces cerevisiae*	30	5.5	Glucose (50–200)	Peptone (2) and ammonium sulfate (4)	18–94	5.1–91.8	Vallet et al. 1996
L-041-*S. cerevisiae*	30 or 35	–	Sucrose (100)	Urea (1) or ammonium sulfate (1–2)	24	25–50	Leticia et al. 1997
181-*S. cerevisiae* (aerobic)	27	6.0	Glucose (10)	Peptone (5.0)	40–160	–	Todor and Tsonka 2002
UO-1-*S. cerevisiae* (aerobic)	30	5.0	Sucrose (20)	Ammonium sulfate (1)	60–96	–	Camacho-Ruiz et al. 2003
V5-*S. cerevisiae*	24	–	Glucose (250)	–	36	–	Virginie et al. 2001
ATCC 24860-*S. cerevisiae*	30	4.5	Molasses (1.6–5.0)	Ammonium sulfate (0.72–2.0)	24	5–18.4	Ergun and Mutlu 2000
Bakers' yeast-*S. cerevisiae*	30	4.5	Sugar (150–300)	–	192	53 (max)	Roukas 1996
Bakers' yeast-*S. cerevisiae*	28	5.0	Sucrose (220)	Peptone(5) and ammonium dihydrogen phosphate (1.5)	96	96.71	Caylak and Vardar 1996
Fiso-*S. cerevisiae*	30	5.0	Galactose (20–150)	Peptone, ammonium sulfate and casamino acid (10)	60	4.8–40	da Cruz et al. 2003
A3-*S. cerevisiae*	30	5.0	Galactose (20–150)	Peptone, ammonium sulfate and casamino acid (10)	60	4.8–36.8	da Cruz et al. 2003
L52-*S. cerevisiae*	30	5.0	Galactose (20–150)	Peptone, ammonium sulfate and casamino acid (10)	60	2.4–32.0	da Cruz et al. 2003
GCB-K5-*S. cerevisiae*	30	6.0	Sucrose (30)	Peptone (5)	72	27	Kiran et al. 2003
GCA-II-*S. cerevisiae*	30	6.0	Sucrose (30)	Peptone (5)	72	42	Kiran et al. 2003
KR_{18}-*S. cerevisiae*	30	6.0	Sucrose (30)	Peptone (5)	72	22.5	Kiran et al. 2003
CMI237-*S. cerevisiae*	30	4.5	Sugar (160)	Ammonium sulfate (0.5)	30	70 (max)	Navarro et al. 2000
2.399-*S. cerevisiae*	30	5.5	Glucose (31.6)	Urea (6.4)	30	13.7 (max)	Yu and Zhang 2004
24860-*S. cerevisiae*	–	–	Glucose (150)	Ammonium dihydrogen phosphate (2.25)	27	48 (max)	Ghasem et al. 2004
27774-*Kluyveromyces fragilis*	30	5.5	Glucose (20–120)	Peptone (2) and ammonium sulfate (4)	18–94	48.96 (max)	Vallet et al. 1996
30017-*K.fragilis*	30	5.5	Glucose (20–120)	Peptone (2) and ammonium sulfate (4)	18–94	48.96 (max)	Vallet et al. 1996
30016-*Kluyveromyces marxianus*	30	5.5	Glucose (100)	Peptone (2) and ammonium sulfate (4)	18–94	44.4 (max)	Vallet et al. 1996
30091-*Candida utilis*	30	5.5	Glucose (100)	Peptone (2) and ammonium sulfate (4)	18–94	44.4 (max)	Vallet et al. 1996
ATCC-32691 *Pachysolen tannophilus*	30	4.5	Glucose (0–25) and xylose (0–25)	Peptone (3.6) and ammonium sulfate (3)	100	7.8 (max)	Sanchez et al. 1999

After the decision of the yeast was made another decision awaited. This was which type of fermentation we were going to choose for. At first, we didn't know there were different kinds of processes to fulfil fermentation, until we came across studies about receiving the highest output. Time and time again the terms SSF and SHF were mentioned, so we decided to go deeper into that.

SSF stands for simultaneous saccharification and SHF stands for separate hydrolysis and fermentation. Studies have shown that SSF is more effective and more cost effective than SHF. This means in the case of SSF, there is only one reactor. While SHF would need two.

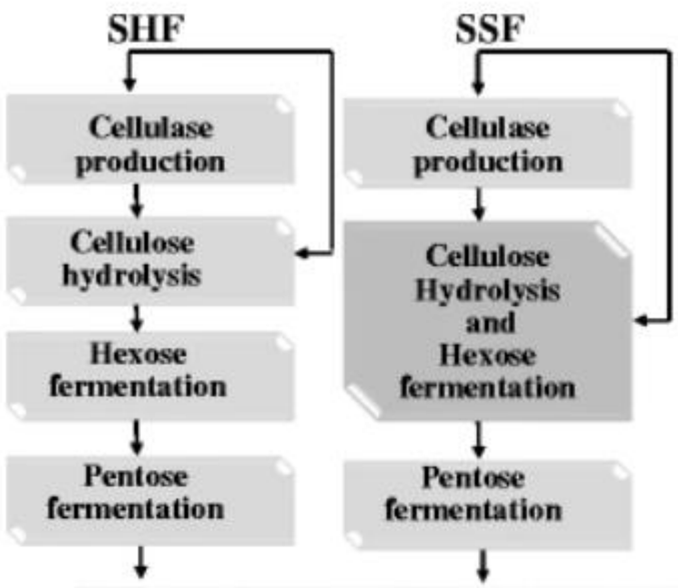

Figure 56. Difference between SHF and SSF [117]

As we know the standards for hydrolysis (pretreatment) are different than the standards for fermentation. The SSF can be carried out in a single bioreactor and provides the advantage of avoiding enzyme inhibition by the glucose because the sugar is continuously withdrawn by the microorganisms and transformed into ethanol, however in this case the temperature cannot usually exceed 35 °C to keep the ethanologenic microorganisms alive, so the enzyme efficiency drops. [118]

In the paper referred to , they report the results obtained using a bio-reaction system, made of two communicating chambers, that allows hydrolysis and fermentation to be carried out simultaneously, but at different temperatures. The hydrolysis process is optimized in the chamber where the biomass is loaded by using the highest temperature compatible with enzyme stability and minimal product inhibition. The fermentation process is continuously fed by the glucose diffusing through the porous barrier. In the fermentation chamber, the yeast converts the glucose into ethanol at 30 °C, which is more suitable for the fermentation process. Therefore, the proposed bioreactor exploits the advantages of both SSF and SHF. This is known as the Viola method, named after the author of this study.

Table 23. SHF and SSF comparison.

Feature	SHF Advantage	SSF Advantage	Hybrid System Implementation
Optimal Temperature for Enzymes	High (40–50 °C)	Lower (due to microbial limits)	✔ Enzymatic hydrolysis chamber operates at high temp (e.g., 50 °C)
Reduced Glucose Inhibition	❌ Glucose accumulates	✔ Glucose is consumed by microbes	✔ Glucose diffuses through porous barrier and is immediately fermented
Enzyme Efficiency	✔ High at 50 °C	❌ Lower at ≤35 °C	✔ Maintained in separate hydrolysis chamber
Fermentation Conditions	❌ Needs cooling step	✔ Single vessel at microbial temp	✔ Separate chamber at 30 °C for yeast activity
Bioreactor Simplicity	❌ Two vessels	✔ One vessel	— Two chambers, but integrated in one system

Our conclusion is to get the most output out of the fermentation process, we should go for the Viola method (mix of SSF and SHF). A good second is the SSF process with the stirred tank reactor, because it has been widely used in applications. And the other benefits I listed with it.

Choice of reactor

Because of our choice to get the best out of both SSF and SHF, we had to find a reactor which makes this possible. Research showed us many reactors, which are listed on the next page:

Table 24 Reactor types for fermentation

#	Reactor Type	Description	Advantages	Used for	SSF / SHF
1	Stirred Tank Reactor (STR)	Motor-driven impeller provides mixing in a stirred vessel.	Good mixing, temperature and pH control; scalable.	Batch and fed-batch; industrial bioethanol production	Both
2	Packed Bed Reactor	Biomass or immobilized microbes packed in a column; liquid flows through.	High biomass retention; good for continuous processes.	Continuous fermentation with immobilized cells	SHF
3	Fluidized Bed Reactor	Biomass particles suspended by upward liquid flow.	Excellent mass and heat transfer; avoids clogging.	Continuous fermentation; particulate substrates	SHF
4	Airlift Reactor	Uses air to circulate liquid and mix contents.	Low shear; energy-efficient mixing.	Aerobic fermentation; fragile cells	SHF / aerobic SSF
5	SSF Reactor	Combines enzymatic hydrolysis and fermentation in one vessel.	Reduces glucose inhibition; cost-effective.	Lignocellulosic bioethanol	SSF
6	Consolidated Bioprocessing (CBP) Reactor	Engineered microbes perform hydrolysis and fermentation simultaneously.	Highly integrated; lower process complexity.	R&D stage; future of biofuel production	SSF
7	Hybrid Dual-Chamber Reactor (Viola System)	Two chambers: one for hydrolysis, one for fermentation.	Optimized enzyme & yeast conditions; avoids glucose inhibition.	High-efficiency lignocellulosic ethanol production	Hybrid SSF/SHF

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Our group proposes two reactors which both are feasible in a real life environment. If simplicity and cost effectiveness are the most important results, we firmly believe that the standard SSF reactor is the most promising. Of course the viola method is not possible with this kind of reactor. If you're looking for optimized performance, especially when dealing with temperature-sensitive enzymes and microbes. The Hybrid Dual Chamber based on the study done by Viola [118] is the most promising. It also turns out to be the most time effective because of the simultaneous happening of the fermentation and hydrolysis.

We have made a summary of the whole timeline, if the latter option would be used. This will give the reader an idea about the time needed to get the end produce:

Table 25 Process phases for fermentation with the Viola method (Hybrid Dual Chamber reactor)

Process Phase	Typical Duration	Details
Enzymatic hydrolysis (chamber 1)	24 – 48 hours	Carried out at 45–50 °C for optimal enzyme activity.
Fermentation (chamber 2)	24 – 48 hours (in parallel)	Starts almost immediately; glucose diffuses through the barrier and is continuously fermented.
Total process time	**48 – 72 hours**	Since hydrolysis and fermentation run simultaneously, only the longer step determines the duration.

- Faster than traditional SHF, where times add up (e.g. 48 h + 48 h = 96 h).
- In the Viola dual-chamber system, hydrolysis and fermentation occur simultaneously but under optimal separate conditions.
- Result: shorter total time (48–72 h) with better efficiency.

Analysis:

To end the general process we did a **TRL (technology readiness Level)**, this contains multiple factors such as the economic, social view etc. This gives us a clear idea of this technology and makes it easier to compare to other technologies.

Environmental Sustainability:

GHG Reduction: Moderate to high when replacing gasoline

Energy Efficiency: Lower than biogas (around 35-45% efficiency)

Water Impact: Higher water consumption than biogas production

Waste Reduction: Good, but produces stillage requiring further processing

Carbon Footprint: Positive but less favorable than biogas due to energy-intensive distillation

Economic Viability:

Capital Investment: Moderate to high

Operating Costs: Moderate, with significant energy costs for distillation

Revenue Streams: Primarily ethanol, with potential for co-products

Payback Period: 7-10 years

Market Readiness: Commercially established

Scalability: Good, but economies of scale favor larger installations

Technical Feasibility:

TRL: 8-9 (commercial to fully commercial)

Process Complexity: Moderate to high, especially with pretreatment requirements

Conversion Efficiency: Enzymatic saccharification can yield up to 11.9 g/L of

bioethanol

Adaptability: Requires different approaches for starchy vs. lignocellulosic

components

Infrastructure: Requires specialized equipment and expertise

Social Considerations:

Job Creation: Moderate

Rural Development: Good potential for agricultural integration

Energy Security: Contributes to liquid fuel independence

Public Acceptance: Generally positive

Regulatory Compliance: Well-established frameworks

10.5.3 Output

In the table underneath are 2 different yields to be found. The first yield means 23,58 grams of bioethanol can be produced per liter of mixture. The mixture contains the potato waste, water and other produce necessary for the fermentation such as yeast and enzymes. The second yield is purely based on the mass of potatoes. Meaning that per ton of potato waste, 260 – 280 Liters of bioethanol is produced. Underneath the yields the references to the studies can be found which led us to those yields.

Table 26. Output Table

Product	Yield	Energy content
Bioethanol	23,58 g/L (when pretreated with enzymatic hydrolysis) [119]	23.4 - 26.8 MJ/kg
Bioethanol	260 – 280 Liters per Ton [120]	23.4 - 26.8 MJ/kg

Today bioethanol is used as a substitute for fossil fuels. The most used application is the mixture of petrol and bioethanol, 90% petrol and 10% bioethanol. This causes to lower the greenhouse emissions compared to the normal use of petrol. Underneath you can find some of the real-life applications of bioethanol today:

- Petrol engines (the mixture of petrol and bioethanol)
- Fuel for generators and cogeneration systems (heat and electricity supply)
- Can be used as feedstock in the chemical industry

10.5.4 Advantages/Disadvantages

Advantages

- Bioethanol has a high-octane number (octane number describes the efficiency of gasoline)
- It has a low boiling point
- Water discharged from the process does not harm the environment.
- It improves energy safety

Disadvantages

- Land use
- High water usage
- Soil degradation
- Possible impact on food prices
- Limited environmental benefit (still not completely green)

Conclusion

The disadvantages are caused by the agricultural aspects, such as the growing and watering etc. While the advantages go far wider, this makes bioethanol a great tool to use for the electrification of the world. And thus make the world less dependent on fossil fuels. The disadvantages based on the agricultural aspects, are not to be taken into account. Purely because we use the waste of biomass that would be grown anyhow.

Cost analysis:

To start this chapter off, we want to say that the next calculation is based on studies and rough estimates. Nevertheless is this calculation a good tool to indicate the initial investment and the revenue. The next summary is basically a summary of the whole process, and the most expensive components per process step.

Process steps and key cost components

Table 27 *Process steps and key cost components* ***[121] [122]***

Process Step	Key Cost Components
Pretreatment (enzymatic hydrolysis)	Enzymes (e.g. cellulase, hemicellulase), heating energy, pretreatment reactor
Viola Dual-Chamber Reactor System	Investment cost (CAPEX) for dual reactor setup, porous membrane/barrier, temperature control
Fermentation (S. cerevisiae)	Yeast cost, nutrient supply, pH regulation, sterilization, agitation, reactor operation
Product Recovery (Ethanol Distillation)	Steam energy, cooling water, distillation columns, condensers
Waste Treatment	Residue handling, wastewater treatment, optional anaerobic digestion
General Costs (Operational + Fixed)	Raw materials, labour, maintenance, building costs, utilities, permits, depreciation

Estimated input prices

The next step is based on rough estimates, the prices can also depend from different suppliers. We estimated the input prices, those costs are made by everything that goes into the process. This can go from water to energy to labor etc. The low energy prices can be led back to the fact that we are an industrial application.

Table 28. Estimated input prices

Input	Rough Estimated Price
Biomass (Potato waste)	Free
Enzymes (cellulase + hemicellulase)	€1 – €5 per kg of active enzyme
***Saccharomyces cerevisiae* yeast**	€2 – €6 per kg of dry yeast
Water and utilities	€1 – €2 per m^3
Energy (electricity/steam)	€0.05 – €0.12 per kWh
Labor and maintenance	10–15% of capital investment per year
Viola reactor (CAPEX estimate)	€1500 – €2500 per m^3 of reactor volume

Simplified cost calculation

Table 29. Simplified cost calculation [123]

Parameter	Value
Biomass input	22 000 tons/year
Ethanol yield	260 - 280 Liters per ton [120]
Annual ethanol output	€ 6 160 000 Liters/year (22 000 * 280)
Total operating cost (OPEX)	€ 2 420 000 per year
Capital cost (CAPEX depreciation)	€ 900 000 per year

Ethanol price/liter

All of this information gives us the chance to go even further and calculate a price for the ethanol. Important to know is that the CAPEX depreciation period of 10 years, which is the standard for industrial bioethanol plants.

Cost per Liter = **(€2,420,000+€900,000) / €6,160,000 ≈ €0.54**

Price comparison

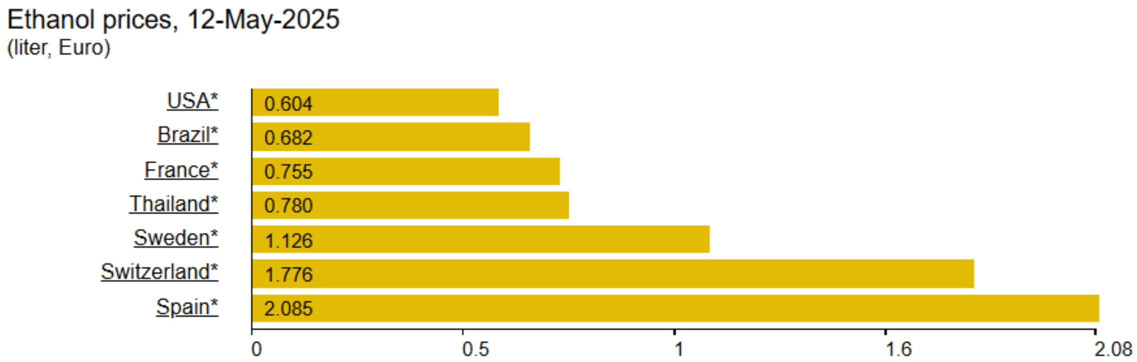

Figure 57. Ethanol prices around the world [124]

Our conclusion is that our price per liter bioethanol (rough estimate) makes our project very feasible and thus a realistic choice. The graph also shows our bioethanol will be able to compete with other bioethanol companies due the price.

10.5.5 Companies

Here we did some research about where this technology already has been applied in real life scenarios. This way we will try to find out what is possible and even more what is impossible. We will also try to go even further and find out what the size of such a factory would be. Because one of the goals is to see if it is feasible to apply this with local Finnish farmers.

Sugar company Anklam

This is a German factory which makes sugar from beets. From what we have read, we think the fermentation process of beets is quite comparable to the one of potatoes. Research shows that in only 132 days, The production has hit 66 000 m^3 of bioethanol. This is the byproduct of the processing of 1,6 million tons of beets, which were converted into 130 000 tons of sugar.

Companies that solely use potato waste haven't been found, although there is a company Royal Cosun. That is looking into it, but they also mainly focus on beets and other biomass waste. More information isn't to be found about this company

Ideally, we would have found a smaller company, so we could go deeper into the smaller "factories". But this is still a work in progress. We haven't read anything about limitations, especially scale wise. So, our hypothesis is that small plants could be possible, but the big question is, if it is economically possible. And maybe we should centralize the potato waste more so we could make a bigger plant. Those questions will be answered if this is the chose technology to be. [125]

11 Comparison and final decision

Comparison/ranking of technologies by Team Potato

Below is a table of the different technologies that were analyzed. These results are our approximations based on the relevant research papers that were found. Starting with the Technology readiness level (TRL), this is a measure of how commercially available the technology is. Rated from 0 meaning the technology is nonexistent and 10 being fully commercially available.

Technology	1 - 10 TRL	Commercial Status	Key advantages	Key challenges	Scale	Payback period	Capital investment	Energy efficiency
Anaerobic digestion	9	Fully commercial	Multiple outputs, carbon sequestration	High temperature requirements	Every scale is possible, with a higher efficiency at larger scales	5-12 years	High	79%
Fermentation	8-9	Commercial	Liquid fuel production, established market	Feasibility different pretreatments, Energy intensive distillation	Every scale is possible, the larger the more interesting	7-10 years	Moderate to high	26 - 28 %
Pyrolysis	7-8	All components are available	3 usable outputs Bio oil, syngas and biochar (also some other chemicals), can be made modular	Requires: pre processing of waste (drying and cutting), Energy intensive due to high T (not as high as gasification), Requires skilled labour (controlled environment)	Becomes more interesting scaled up to a certain point where the process loses efficiency	<10 years	High	due to having 3 outputs it can go above 75%
Gasification	5-7	Gasification of potato waste possibl but not widely adopted	Syngas --> multiple resources, small land use	Gasification --> very advanced method making it expensive. For efficient conversion, feedstock needs low moisture content --> not the case with potatoes	Every scale is possible	5-15 years	High	55% and higher
Transesterification (potato peel catalyst)	5-6	Lab/Demonstration	Waste valorization, low-cost green catalyst	Feedstock limitations, non-reusable catalyst	Limited to pilot-scale projects	7-10 years	Low to Moderate	30% - 40%

Figure 58 Comparison/ranking of technologies

Why are these criteria relevant?

1. Technology readiness level (TRL): Rated form 0 meaning the technology is nonexistent and 10 being fully commercially available.

2. Commercial status: The technology needs to work in real-world conditions and a fully commercial or at least close-to-market technology means proven performance and lower technical risk on top of being commercially available.

3. Scale: The plant size needs to match the local feedstock volume.

4. Payback Period: The ideal is to have a low payback period to ensure biofuels are economically competitive.

5. Capital investment: A high-cost system might not be realistic unless there’s strong financial backing.

6. Energy Efficiency: Probably the most important criteria because of the interest in good sustainability.

7. Regionality: This criterium describes the local use of biofuel, as explained below. The excel does not contain this criterium, but we did take the local current applications into consideration for the final ranking.

1. Technology readiness level (TRL):

Anaerobic digestion is at TRL 9, fully mature and operational in commercial settings.

Fermentation follows closely with a TRL of 8–9, already in industrial use for various biofuels.

Pyrolysis systems are at TRL 7–8 but still require adaptation for consistent use with potato waste.

Gasification is at TRL 5–7, particularly limited by feedstock challenges.

Transesterification using waste-derived catalysts remains at TRL 5–6, with development limited to lab or demonstration environments.

TRL	
01	ANAEROBIC DIGESTION
02	FERMENTATION
03	PYROLYSIS
04	GASIFICATION
05	TRANSESTERIFICATION

Figure 59 TRL Ranking

2. Commercial status:

COMMERCIAL	
01	ANAEROBIC DIGESTION
02	FERMENTATION
03	PYROLYSIS
04	GASIFICATION
05	TRANSESTERIFICATION

Figure 60 Commercial Status Ranking

Anaerobic digestion is a fully commercial technology with widespread deployment across Europe.

Fermentation is also commercially established, particularly in the bioethanol industry.

Pyrolysis systems are available but less widely implemented.

Gasification, though technically feasible, is not yet widely adopted for potato waste.

Transesterification using potato-based catalysts remains at the laboratory or demonstration stage.

3. Scale:

Anaerobic digestion can be implemented at a wide range of scales, from small farms to large industrial plants, with improved efficiency at larger sizes.

Fermentation and gasification are also scalable but may require more stringent process controls and feedstock conditioning.

Pyrolysis is scalable to a point but becomes less efficient at large scale.

Transesterification is currently limited to pilot-scale research.

SCALE	
01	ANAEROBIC DIGESTION
02	FERMENTATION
03	GASIFICATION
04	PYROLYSIS
05	TRANSESTERIFICATION

Figure 61 Scale Ranking

4. Payback Period:

PAYBACK PERIOD	
01	FERMENTATION
02	PYROLYSIS
03	TRANSESTERIFICATION
04	ANAEROBIC DIGESTION
05	GASIFICATION

Figure 62 Payback Period Ranking

Fermentation, pyrolysis, and transesterification have payback periods generally below 10 years, depending on system size and integration.

Anaerobic digestion shows a moderate return on investment, typically between 5 and 12 years.

Gasification systems, due to higher complexity and capital costs, show longer payback periods, potentially up to 15 years.

5. **Capital Investment:**

Transesterification has the lowest capital cost, especially at experimental scale.

Fermentation requires moderate to high investment, particularly for distillation and pretreatment units.

Anaerobic digestion, pyrolysis, and gasification all require high capital input, mainly due to specialized equipment, temperature control systems, and, in some cases, feedstock preparation.

CAPITAL INVESTMENT	
01	TRANSESTERIFICATION
02	FERMENTATION
03	ANAEROBIC DIGESTION
04	PYROLYSIS
05	GASIFICATION

Figure 63 Capital Investment Ranking

6. **Energy Efficiency:**

ENERGY EFFICIENCY	
01	PYROLYSIS
02	ANAEROBIC DIGESTION
03	GASIFICATION
04	FERMENTATION
05	TRANSESTERIFICATION

Figure 64 Energy Efficiency Ranking

Pyrolysis offers high energy efficiency (above 75%) due to the multiple useful outputs, including syngas, bio-oil, and biochar.

Anaerobic digestion also performs well (~79%) with methane-rich biogas.

Gasification can exceed 55% efficiency under optimal conditions.

Fermentation is less efficient due to energy-intensive distillation.

Transesterification is the least energy-efficient (30–40%), reflecting both process limitations and current research-stage development.

7. Regionality -- Biogas

These days, we know that energy is at the heart of a desire to be more eco-responsible. There are many ways of replacing fossil fuels, including wind turbines and solar panels.
That's why the region of Ostrobothnia in Finland has also decided to embark on this adventure, with its already well-established ecological conscience as its trump card.

For example, biogas is already used in Finland for public transportation. In 2017 Vaasa started using twelve busses driving on biogas. These busses substitute around 280 000 liters of fossil fuel diesel. This biogas is produced near Stormossen and is made from household waste and wastewater from Vaasa.
[126] [127]

It is also used in Vaasa by the Vaasan Voima power plant for combined heat and power (CHP). The biomass used is sourced from the local region in a radius of 100km to reduce transport emissions.
[128]

Final decision

Based on the criteria discussed in this report, a final ranking was made based on a value weight matrix as seen below.
The highest scoring technology is anaerobic digestion with 24 points. On top of scoring the most points it receives 3 bonus points for regional relevance coming out on 27.
Making it a clear winner.
Fermentation being a strong second due to its widespread implementation and being a mature and trustworthy technology.

Table 30. Rating the technologies.

Technology	Technology readiness level	Commercial status	Scale	Payback Period	Capital investment	Energy Efficiency	Final score
Anaerobic digestion	5	5	5	2	3	4	24 +3 27
Fermentation	4	4	4	5	4	2	23
Gasification	3	3	3	1	1	3	14
Pyrolysis	2	2	2	4	2	5	17
Transesterification	1	1	1	3	5	1	12

12 Project Conclusion

During the EPS project spring 2025 we chose for the Power of Potatoes project. The project was divided into six work packages (WP). Our focus was on WP2 with the option to start on the next package. Each team member took upon them a technology to dive into, this worked out great since this divided the work equally. Despite this we were always ready to help each other out if help was needed.

One weakness our team had is that we were not all that familiar with the biofuel sector. This made it initially hard to familiarize ourselves with the technologies and processes. This made it so that our project had a slow start and we started off behind schedule.

Something we would do differently in future projects would be to hold more physical meetings. As now we have almost exclusively online meetings and these can be hard to coordinate work in.

Throughout the project we were looking for ways to improve sustainability of applied technologies, we thought of having local farmers use their own refinery on a small scale for self-use to cut out transportation costs. But because of the economy of scale, we found out that a centralized option would make more sense.

The deliverables from this project were very theoretical, we would have preferred a little bit more practical. Something that we could put our hands on, something more tangible that we could present and work around.
The teambuilding activities helped us out in getting to know each other better and to improve our cooperation.

Thanks to the courses we were allowed to follow, namely Project Management and cross-cultural communication. We were able to develop our management and communication skills that helped bring the project to a successful conclusion.

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