POWER OF POTATOES

Yrkeshögskolan Novia – Serie R – Rapport 2026.

WP2: Rapport

Technical evaluation of side streams from the potato industry as an energy feedstock: technical methods for renewable energy in Ostrobothnia

Medfinansieras av
Europeiska unionen

ÖSTERBOTTENS FÖRBUND
POHJANMAAN LIITTO

YRKESHÖGSKOLAN
NOVIA

Biniam Tefera (Yrkeshögskolan Novia)
Projekt: Power of Potatoes.
WP2: Technical evaluation of side streams from the potato industry as an energy feedstock: technical methods for renewable energy in Ostrobothnia

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Novia Publikation och produktion, serie R: Rapporter 11/2026
ISBN: 978-952-7526-80-4 (Online) ISSN: 1799-4179

Abstract

This report is part of Power Of Potatoes project financed by Just Transition Fund (JTF) in collaboration with the Regional council of Ostrobothnia and Novia University of Applied Sciences. This report examines the technologies available for converting massive volumes of high moisture potato side-streams into renewable bioenergy carriers. The objective was to evaluate industrial potato peel and map available conversion technologies in order to identify the most profitable and energy-efficient processes for regional deployment in Ostrobothnia. The method consisted of reviewing substrate pretreatment requirements, assessing biological and thermochemical conversion pathways, and applying a Technology Readiness Level framework to rate feasibility of commercial maturity. The results show that anaerobic digestion consistently serves as the most viable and commercially mature technology for wet potato residues, operating at a readiness level of 9. Because anaerobic digestion processes wet biomass directly, it completely bypasses the massive energy penalties associated with dehydrating raw potato peels. By contrast, standalone thermal processes, such as dry pyrolysis and gasification, require energy-intensive drying phases that severely compromise net energy efficiency. The results also demonstrate that combining primary conversion technologies into cascading biorefinery models positively improves financial viability. Several analyzed thermal pathways, including hydrothermal carbonization, circumvent dehydration needs entirely, supporting their status as emerging solutions for wet agricultural residues. The main conclusion is that favorable energy conversion architectures are characterized by matching high-moisture feedstocks directly with wet-pathway technologies, minimizing thermal drying dependencies, and applying integrated approaches to generate reliable revenue streams.

Key words: Potato Side-streams, technology Assessment, Benchmarking, Optimization

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List of Abbreviations

ABE Acetone Butanol Ethanol.

AD Anaerobic Digestion.

AI Artificial Intelligence.

bcm billion cubic meters.

BMP Biochemical Methane Potential.

BREF Best Available Techniques Reference Document.

CAPEX Capital Expenditures.

CH4 Methane.

CO2 Carbon dioxide.

DoE Design of Experiments.

EBA European Biogas Association.

H2 Molecular hydrogen.

HTC Hydrothermal Carbonization.

HTL Hydrothermal Liquefaction.

IRR Internal Rate of Return.

ISO International Organization for Standardization.

ISR Inoculum to Substrate Ratio.

JTF Just Transition Fund.

LCFAs Long chain fatty acids.

NPV Net Present Value.

TA Total Alkalinity.

TDT Technical Digestion Time.

TRL Technology Readiness Level.

VDI Verein Deutscher Ingenieure.

VFAs Volatile Fatty Acids.

1. Introduction

The global transition toward sustainable, decarbonized, and circular bio-economies demands rigorous evaluation of abundant, low-cost agricultural and industrial wastes for renewable energy generation (Abad et al., 2019). The commercial potato processing industry generates very high volumes of organic by-products driven by the increasing demand for processed foods such as chips, fries, and starches. Food processing industries are using different potato peeling methodology employed at the industrial scale ranging from abrasive and lye peeling to advanced high-pressure steam peeling. These methods result in potato peel waste ranging between 15% and 40% of the initial raw tuber mass (Awogbemi et al., 2022).

Historically, this massive organic agricultural residue has been downgraded to low-value, suboptimal applications. Industrial producers have primarily relied on direct land application, sale as low-grade animal feed, or disposed of in municipal landfills (Awogbemi et al., 2022). However, these traditional waste management strategies present profound environmental and economic liabilities. The anaerobic decomposition of high-moisture potato peel in landfills generates uncontrolled high emissions of methane, a potent greenhouse gas (IPCC, 2006). In addition to the environmental impact of decomposition, economically, disposal incurs significant transportation and logistics fees, representing a pure capital loss for processing facilities.

In recent years, the unique physicochemical composition of potato peel has repositioned it from an industrial waste to a promising, zero-cost feedstock for advanced biorefinery operations. Because potato peel does not compete with global food security pathways in the same manner as primary agricultural crops (such as corn or sugarcane), its utilization aligns perfectly with the mandates of second-generation biofuel production (Pandiyan et al., 2019). This report exhaustively evaluates the current technologies available for converting potato peel into distinct bioenergy carriers including bioethanol, biobutanol, biomethane, biohydrogen, syngas, bio-oil, methanol, biodiesel (via transesterification), and solid hydrochar. The analysis rigorously rates each conversion process technologies based on its Technology Readiness Level (TRL), commercial status, operational scale, payback period, capital investment, energy efficiency, and product output, relying strictly on empirical data derived from scientific literature.

1.1 Overview of the Power of Potatoes Project

The increasing global energy demand coupled with the rapid generation of agricultural waste presents a critical challenge for sustainable industrial development. The "Power of Potatoes" project is in direct alignment with Finland's national development strategies which aims to address these challenges by converting challenging agricultural residues into high-value energy carriers. Potato side streams represent a massive and underutilized agricultural residue that generates significant environmental pollution if left to decompose in conventional landfills. Agricultural sector can reduce greenhouse gas emissions by redirecting these side-streams into closed-loop energy recovery systems, At the same time, this can help to offset fossil fuel dependency by producing renewable energy.

1.2 Objectives and Scope

The primary objective of this work package is to provide a comprehensive technological evaluation of the methods available for converting potato side-streams into viable energy sources. Evaluation contains a detailed mapping of biological and thermochemical conversion technologies, identifying their operational requirements, and measuring their respective fuel yields. In addition, a preliminary techno-economic assessment designed to determine the most profitable and energy-efficient configurations for industrial deployment are included in the scope of PoP.

Standardization of process models and digital benchmarks used to ensure that the selected waste-to-energy architectures can be reliably scaled to meet regional energy demands.

2. Infrastructural Context

2.1 Biogas Infrastructure in European Regions

The European Union currently operates as the global leader in the deployment of anaerobic digestion technology for renewable electricity and gas production. Current statistical assessments indicate that EU-27 gas consumption reached 332 billion cubic meters (bcm), and 273 bcm still imported. Recent reports also highlight the urgent need to focus on regional renewable energy solutions to reduce energy dependency. Biogases offer an alternative option to reducing energy dependence while increasing the competitiveness of Europe in its ambition to phase-out of fossil fuels. According to The European Biogas Association (EBA) report, Europe's dispatchable power generation capacity has fallen markedly, from 424 GW in 2012 to around 380 GW in 2023, despite the growing need for flexibility. As a clean, dispatchable energy source, Biogases play essential role for balancing the grid during extended periods of low solar and wind production specially in Northern part of Europe during winter seasons.

Combined production of biogas and biomethane in Europe has grown modestly to reach 22 bcm by 2024 as compared to 21.7 bcm in 2023. The projected growth is mostly from the EU-27 countries (19 bcm). Countries like Germany and Italy dominate this production due to their well-established systems and a regulatory framework supporting the continuous processing of agricultural residues and energy crops (Capodaglio et al. 2016). However, the infrastructure is now undergoing a critical transition, moving away from dedicated energy crops like maize silage toward the utilization of pure agricultural side streams and industrial food waste to avoid competition with food production networks (Almeida et al., 2023).

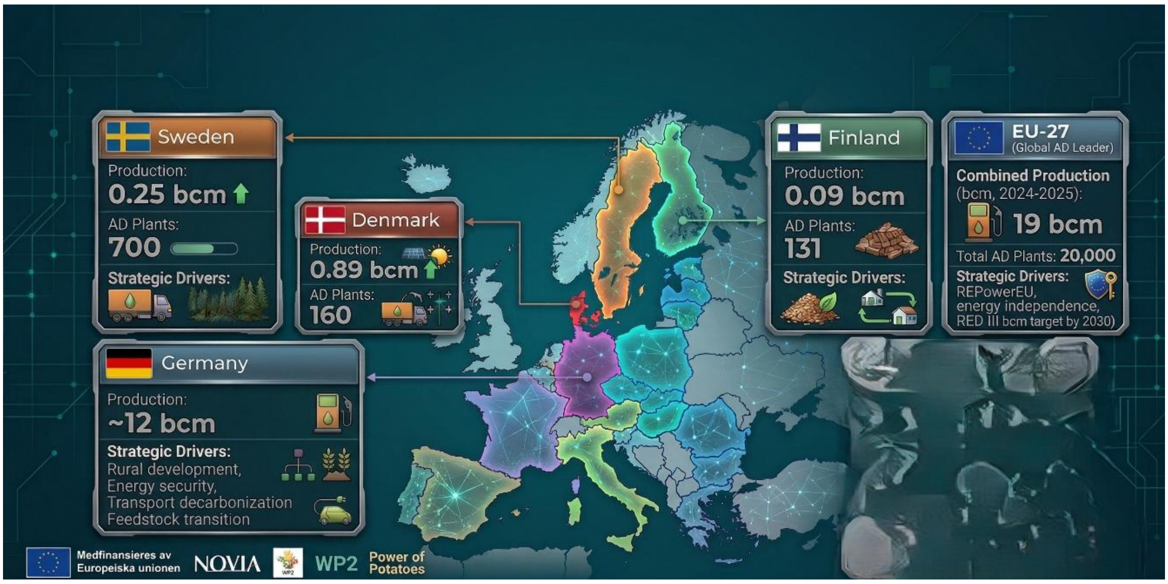


Figure 1: Biogas/Biomethane infrastructure and production volumes across European regions (2024-2025)

2.2 Regional Focus on Finland and Ostrobothnia

Within the Nordic context, Finland has developed a highly advanced waste-to-energy infrastructure operating approximately ten large-scale waste-to-energy power plants under municipal and industrial control (EastCham Finland, 2021). In the specific region of Ostrobothnia, recent developmental focus has shifted toward farm-scale technologies capable of processing challenging local feedstocks, including potato residues and greenhouse waste contaminated with inorganic materials (Makkonen, 2025). The regional production potential in specific Ostrobothnia nodes has been calculated at volumes ranging from 24 to 59 tons of potato peel waste, necessitating the utilization of specialized, low-maintenance reactor configurations such as the Slope Bottom Reactor to achieve profitable localized energy recovery (Makkonen, 2025).

3. Technological Mapping and Evaluation

3.1 Substrate Characteristics of Potato Side Streams

The successful conversion of potato side-streams is directed by a thorough understanding of natural physicochemical properties. Potato is characterized by extremely high moisture content. Potato peel moisture content is ranging between 77% and 85%, which heavily influences the selection of downstream processing technologies (Almeida et al., 2023). The organic matrix is composed primarily of carbohydrates between 46.2% and 77.4% on a dry weight basis. Starch constitutes a significant portion, alongside complex structural polymers including lignin (21.6% to 32.9%) and cellulose (Awogbemi et al., 2022). Additionally, potato side streams contain low levels of lipids and proteins. Potato peel contains glycoalkaloids such as alpha-solanine, which can actively inhibit direct microbial degradation if not properly managed during the pre-treatment process (Elhag et al., 2023).

3.2 Pretreatment Methods

The potato peel's tough lignocellulosic structures and inhibitors require an advanced and proper pretreatment method to break down. The bioavailability of biomass can be improved through several pretreatment methods. Amongst the 'physical pretreatment' processes, offering mechanical grinding or ultrasonication has been acclaimed in the literature (Sagar et al., 2024). These processes successfully increase the accessible surface area of the biomass enabling more contact during digestion phase by the microbes. Making use of diluted sulfuric acid (e.g. 1% concentration) is a very efficient method for the conversion of complex carbohydrates into fermentable sugars (Soni et al 2023). Another option is the use of biological pretreatments by using specific strains of amylase-producing fungi such as *Rhizopus stolonifer* to hydrolyze the starches. This option offers an eco-friendly mechanism to hydrolyze starches without generating the toxic secondary byproducts commonly associated with severe chemical hydrolysis (Elhag et al., 2023).

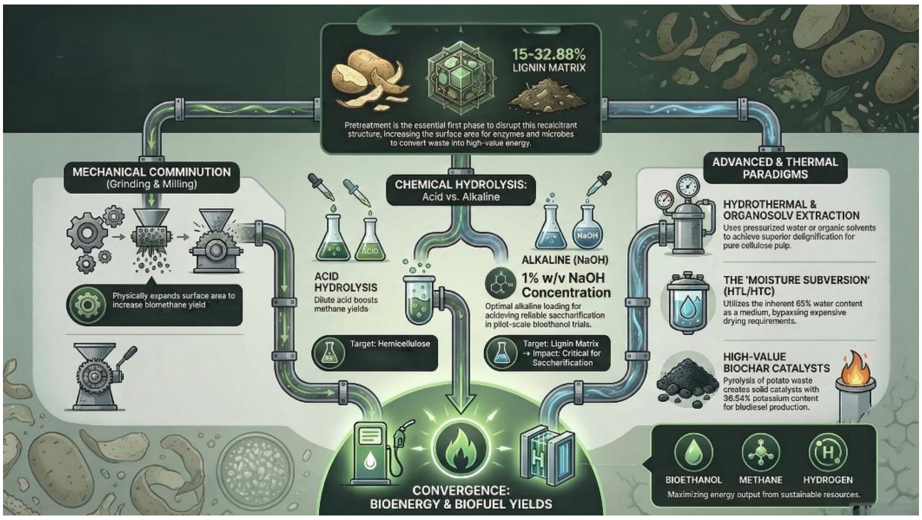


Figure 2: Pretreatment of Potato Side-stream

Although potato side streams are inherently rich in fermentable starch, their full bioenergy potential is locked behind rigid, recalcitrant lignocellulosic structures and complex cell walls (Awogbemi et al., 2022). To maximize fuel yields, pretreatment methods are categorized into three strategic pillars: mechanical, chemical, and advanced physicochemical methods.

Mechanical comminution, such as grinding or milling, serves as an operational baseline by physically fragmenting the biomass to exponentially expand its exposure surface area. This structural disruption grants microbes and enzymes direct access to internal starch polymers, significantly reducing the required retention time in the digester (Sagar et al., 2024).

Chemical approach evaluates the use of dilute acids or alkaline solutions to actively solubilize the biomass matrix, essentially converting solid recalcitrant matter into a highly fermentable liquid (Liang et al., 2024).

For absolute optimization, advanced methods like hydrothermal pretreatment provide high performance solutions designed to overcome the specific recalcitrance of the cell wall polymers. By operating under pressurized high temperature conditions without the need for chemical additives, this method mimics an industrial scale pressure cooker to trigger starch gelatinization and thoroughly dismantle the crystalline structure of the biomass (Soni et al., 2023). This pretreatment creates suitable precondition for subsequent anaerobic digestion, which is crucial for high volume throughput in a farm scale reactor. Essentially, the choice of pretreatment system is a delicate balancing act between achieving the highest possible biological yield and minimizing the energy input as much as possible. As facilities undergo new development phases, it is essential to recognize that these pretreatment options determine whether downstream conversion options, such as dark fermentation or bioethanol synthesis, will be economically viable (Almeida et al., 2023).

4. Biochemical Conversion Technologies

4.1 Anaerobic Digestion and Biogas Production

Anaerobic Digestion (AD) remains the most mature and reliable biochemical pathway for converting high moisture potato side-streams into methane-rich biogas. Unlike a single chemical reaction, anaerobic digestion is a complex, symbiotic cascade that relies on four distinct microbial phases to degrade the potato peel: hydrolytic, acidogenic, acetogenic, and methanogenic (Almeida et al., 2023).

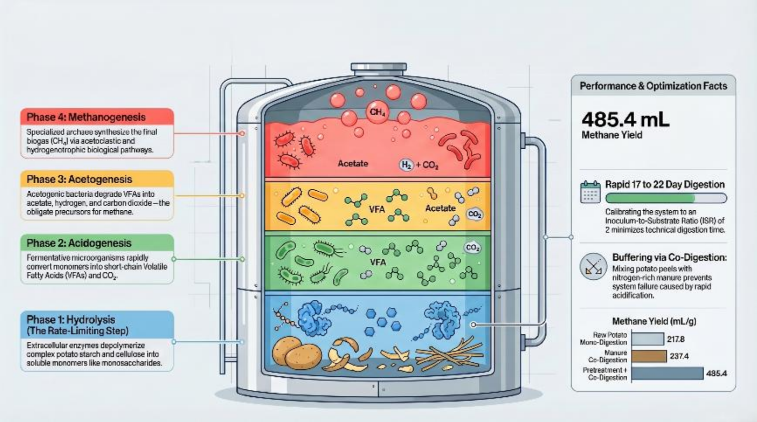


Figure 3. Anaerobic Digestion and Biogas Production

In the first hydrolysis step, hydrolytic bacteria secrete extracellular enzymes like amylases, cellulases and proteases. The enzymes that are secreted assist in degrading the resistant and insoluble organic components of the potato peel, such as starch, cellulose, and proteins, into soluble monomers including monosaccharides, amino acids and LCFAs (Achinas et al., 2019; Ren et al., 2018). According to Ren et al. (2018), water dependent cleavage is known to be rate limiting step of the whole AD process because the complex biopolymers in the potato peel are highly recalcitrant

Subsequently, in the acidogenesis (or acidification) stage, acidogenic and fermentative microorganisms rapidly absorb these soluble monomers, converting them into short-chain Volatile Fatty Acids (VFAs). The output of this second stage is predominantly propionic, butyric, and valeric acids, alongside trace alcohols, carbon dioxide (CO2), and molecular hydrogen (H2) (Achinas et al., 2019; Pandey et al., 2020).

Acetogenesis is the third phase which involves further degradation of the generated VFAs and alcohols by acetogenic bacteria. This dehydrogenation process yields acetate (acetic acid). In addition, this process has an output of supplementary CO2 and H2, which function as the obligate precursors for the biological conversion stage (Pandey et al., 2020; Stams & Plugge, 2009).

In the final methanogenic phase, methanogenic archaea synthesize the target biogas. This last phase is governed by two primary biological pathways. This final phase of AD best described as two processes. On one hand acetoclastic (or acetotrophic) methanogens convert the accumulated acetate directly into methane (CH4) and CO2, whereas hydrogenotrophic methanogens reduce CO2 by utilizing H2 gas from the previous acetogenesis phase to generate CH4 and water (Stams & Plugge, 2009; Wang & Lee, 2021).

The baseline mono-digestion of raw potato peels yields approximately 217.8 mL of methane per gram of volatile solids added (Achinas et al., 2019). To optimize this output and buffer the system against rapid acidification, co-digestion with nitrogen-rich substrates like cow manure or sheep manure is heavily utilized, shifting the carbon-to-nitrogen ratio to favorable operational limits and increasing methane yields to 237.4 mL per gram of volatile solids (Adeleye et al., 2022). Applying the aforementioned acidic or enzymatic pretreatments prior to co-digestion has been documented to elevate these methane yields dramatically, reaching peak productions of 485.4 mL per gram of volatile solids (Achinas et al., 2019). To maintain process stability and speed up operations, kinetic control is essential. By carefully calibrating the system to an optimal Inoculum-to-Substrate Ratio (ISR) of 2, we can maximize the degradation rate and minimize the Technical Digestion Time (TDT) to a very rapid 17 to 22 days.

4.2 Bioethanol Synthesis

Bioethanol synthesis of potato side-streams requires the precise fermentation of glucose and maltose. Effective physical and chemical pretreatment increases active surface area of the biomass for microbial action. Pretreatment of potato side-stream is followed by introduction of microorganisms such as *Saccharomyces cerevisiae* or *Zymomonas mobilis* to convert the solubilized sugars into ethanol under strict anaerobic conditions (Mazaheri & Pirouzi, 2020). Integration of saccharification and fermentation simultaneously are proven effective processes in reducing overall reactor residence times and minimizing capital expenditure (Chohan et al., 2020). The ultimate volumetric yield of bioethanol is highly dependent on two factors: the severity of the pretreatment phase and the successful removal of fermentation inhibitors generated during acid hydrolysis (Soni et al., 2023).

4.3 Biobutanol Fermentation

Biobutanol has higher energy density and lower hygroscopicity compared to ethanol which makes it superior energy carrier. These made it highly compatible with existing combustion infrastructure. The production of butanol from potato side-stream is achieved via the Acetone-Butanol-Ethanol (ABE) fermentation pathway, strictly utilizing bacterial strains such as *Clostridia acetobutylicum* (Jin et al., 2022). Using organosolv pretreatment and targeted inhibitor removal techniques to potato peel has been shown to yield butanol concentrations reaching 12.6 g/L (Abedini et al., 2020). The primary technical limitation of this technology remains the severe product toxicity associated with butanol accumulation, which forces bacterial death at relatively low solvent titers, thereby demanding continuous extraction protocols (Hijosa-Valsero et al., 2018).

4.4 Dark Fermentation for Biohydrogen

Dark fermentation represents an advanced biological pathway for the direct generation of biohydrogen from organic substrates. This technology uses either mixed microorganisms or specific hyperthermophile strains such as *Thermotoga neapolitana*. The selected microorganism rapidly degrades complex carbohydrates in potato side-stream into hydrogen gas and volatile fatty acids (Mars et al., 2010). Dark fermentation operates at an elevated temperature (hyperthermophile conditions) which significantly accelerates the hydrolysis of the potato starch. This operating condition results in higher net hydrogen production rates compared to standard mesophilic digestion (Salem et al., 2018). While biohydrogen offers a completely zero-carbon combustion profile, the simultaneous accumulation of volatile fatty acids requires a secondary processing stage, such as a coupled methanogenic reactor, to ensure complete energy recovery from the residual liquid matrix (Elhag et al., 2023).

5. Thermochemical Conversion Technologies

5.1 Pyrolysis

Pyrolysis conversion technologies provide rapid decomposition of organic matters into high-density fuels. Dry pyrolysis involves heating dehydrated potato side-stream in an oxygen-deficient environment at temperatures between 400 °C and 700 °C. This thermochemical process produces a mixture of bio-oil, syngas, and solid biochar

(Daimary et al., 2022). The fundamental weakness of applying this specific dry thermal system to raw potato side streams is the immense thermodynamic penalty incurred during the prerequisite drying phase. To achieve process viability, the raw potato peel must be dehydrated from an initial moisture content of around 85% to below 20% moisture before entering the thermal reactor (Almeida et al., 2023).

5.2 Gasification

Gasification operates at significantly higher thermal parameters, typically between 800 °C and 1200 °C. This thermal technology uses a controlled gasification agent to maximize the volumetric output of combustible syngas (Giuliano et al., 2020). While gasification effectively converts the organic matter into a versatile gaseous fuel, it suffers from the same fundamental limitation as dry pyrolysis when applied to raw potato side streams. The requirement to vaporize the inherent moisture content before the high-temperature conversion demands an energy-intensive preliminary drying phase. This severely compromises the net energy efficiency and economic feasibility of the technology (Almeida et al., 2023).

5.3 Integrated Pyrolysis and Gasification

To mitigate the limitations of standalone thermal processes, modern engineering architectures couple pyrolysis and gasification units directly with biological reactors. In a cascading circular bioenergy model, the solid digestate remaining after anaerobic digestion is mechanically dewatered and subsequently processed through a pyrolysis unit (Deng et al., 2020). The thermal energy required to sustain the pyrolysis chamber is provided by combusting a fraction of the generated biogas, while the resulting biochar is recovered as a high-value soil amendment or carbon sink (Maroušek et al., 2020). This dual technology configuration maximizes the total carbon recovery from the potato side-stream while eliminating the disposal costs associated with raw wet digestate (Monlau et al., 2015).

5.3 Hydrothermal Carbonization

Hydrothermal carbonization (HTC) operates as a highly specialized thermal process tailored specifically for wet biomass. This technology operates at temperatures between 180 °C and 250 °C under pressurized water (Funke & Ziegler, 2010). Because HTC maintains water in its liquid state, it eliminates the extensive need of high thermal processes required to vaporize the 80% moisture content inherent to potato peel waste (Catenacci et al., 2022). The primary output is hydrochar, a dense, carbon-rich solid that mimics the combustion properties of fossil coal while possessing excellent characteristics for agricultural soil amendment (Nizamuddin et al., 2017). This technology represents the most energy-efficient thermal pathway for processing raw, high-moisture agricultural residues like potato peel (Wang et al., 2023).

5.4 Hydrothermal Liquefaction

Hydrothermal liquefaction (HTL) bypasses the need for potato side-stream dehydration. This technology operates at more controlled environment, utilizing temperatures between 280 °C and 370 °C and pressures up to 25 MPa (Brindhadevi et al., 2021). Under these subcritical water conditions, the polymeric components of the potato peel are depolymerized and reformed into a heavy, energy-dense liquid biocrude or bio-oil. While HTL successfully recovers the majority of the carbon and energy present in the wet potato matrix, the resulting bio-oil contains high levels of oxygen and nitrogen. These high levels require extensive catalytic hydrotreating before it can be blended with standard petroleum transport fuels (Dimitriadis & Bezergianni, 2017).

6. Chemical Synthesis and Catalytic Upgrading

6.1 Transesterification

The residual lipid fractions present in potato processing wastes, as well as the long-chain fatty acids generated during the acidogenic phase of digestion, serve as excellent precursors for biodiesel production. This process involves sequential recovery of these lipids via enzymatic esterification. Transesterification relies on biocatalysts, such as the lipases secreted by *Rhizopus stolonifer*, to facilitate the conversion into fatty acid methyl esters. This process involves sequential recovery of these lipids via enzymatic esterification. (Elhag et al., 2023). Furthermore, the solid biochar generated from the pyrolysis of potato peels can be chemically activated to function as a highly porous, zero-cost heterogeneous catalyst for these transesterification reactions, effectively closing the material loop within the biorefinery (Daimary et al., 2022). This combined biological and chemical approach yields biodiesel recovery rates approaching 64.8% of the available analytes (Elhag et al., 2023).

6.2 Methanol Synthesis

The gaseous outputs from primary conversion processes can be chemically upgraded into stable liquid fuels, mitigating the storage and transport difficulties associated with raw biogas. Methanol synthesis relies on a process of capturing the carbon dioxide fraction of biogas and reacting it with external renewable hydrogen (Dieterich et al., 2020). The syngas produced by high-temperature gasification technology can be subjected to either catalytic Fischer-Tropsch synthesis or direct methanol synthesis pathways (Kiefer et al., 2021). These power-to-liquid strategies convert the low-value gaseous components derived from potato side streams into highly stable, globally tradable chemical commodities suitable for maritime and heavy transport sectors (Lin et al., 2021).

7. Technology Assessment and Economic Landscape

7.1 Evaluation Methodology and Comparison Criteria

Techno Economic Assessment Matrix is generated for the Power of Potatoes project using a strict comparative framework. The technologies are not categorized arbitrarily. Instead, empirical data extracted from peer reviewed economic models and pilot scale validations were synthesized.

Data Collection and Evidence Weighting

The foundation of this matrix is built by systematically screening the available literature. The studies weighted heavily only if they provided transparent methodologies with detail conversion steps, mass balances, and resulting technological outcomes (Spizzirri et al., 2026).

When evaluating conflicting data regarding yields or profitability, empirical evidence derived from continuous, pilot scale, or industrial demonstration facilities prioritized over theoretical laboratory experiments. This weighting strategy was applied because laboratory conditions rarely account for the operational bottlenecks encountered during large scale deployment (Fotis et al., 2022). If a specific study lacked clarity regarding its capital expenditure assumptions or failed to account for necessary pretreatment penalties, its economic conclusions were weighted lower in the final matrix.

Defining the Comparison Criteria: Technology Readiness Level

Technology Readiness Level metric is used to assess technical maturity on a standard 1 to 9 scale. Technologies are strictly evaluated based on the physical scale at which operators have successfully and continuously run the technology. Technologies operating at level 8 or 9, such as anaerobic digestion, as highly mature because thousands of existing commercial facilities prove their operational reliability globally (Almeida et al., 2023). Conversely, low ratings (level 2 to 3) are assigned to pathways like dark fermentation for biohydrogen. Current literature indicates these processes remain confined to laboratory scale research and face unresolved biological stability issues (Spizzirri et al., 2026).

Defining the Comparison Criteria: Commercial Viability

Commercial Viability and Economic Attractiveness dimension defined (Low, Medium, or High) by aggregating specific financial indicators. The comparison criteria focused primarily on Net Present Value, Internal Rate of Return, and anticipated payback periods (Morero et al., 2024). To achieve a High Economic Attractiveness classification, a technology had to demonstrate a consistently positive Net Present Value and an Internal Rate of Return exceeding standard acceptable discount rates, typically 10%. The technology must achieve this without requiring permanent reliance on heavy government subsidies.

The robustness of these economic indicators against market volatility is considered. The most credible literature utilized applied Monte Carlo simulations to calculate probabilistic ranges for these financial metrics. These simulations actively account for fluctuations such as electricity selling prices, feedstock logistics, and capital expenditure variations (Wang et al., 2024).

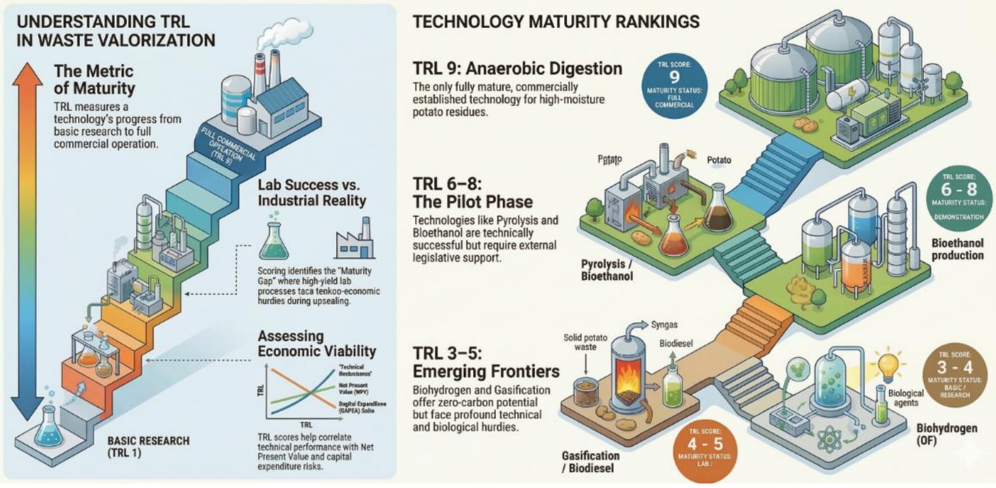
Medium or Low Economic Attractiveness is assigned to technologies that require substantial thermodynamic penalties that reduce profit margins. For example, dry thermal processes are downgraded when applied to high-moisture potato side-streams, as the compulsory latent heat demand for pre-drying markedly increases operating expenditures and can extend payback periods or render projects economically unviable (Almeida et al., 2023).

Synthesis and Limitations

The final matrix represents the intersection of these two distinct criteria. A high readiness level does not automatically guarantee high commercial viability. The analysis strictly separates engineering maturity from financial profitability. Economic models derived from global literature inherently carry variance due to differences in regional regulations, assumed energy tariffs, and localized labour costs. Existing literature provides baseline commercial viability rankings that serve as general industry benchmarks, not precise financial guarantees for the Ostrobothnia region.

7.2 Technology Readiness Level Evaluation

Commercial viability and operational feasibility of emerging industrial technologies are evaluated by standardized metric to assess their developmental stage. Technology Readiness Level (TRL) is a standardized metric which serves as critical benchmark in technology maturity evaluation. TRL functions as a systematic rating framework to indicate the precise feasibility and commercial readiness of a specific technology. Such classification scales typically range from the initial laboratory research phases at the lowest levels to fully established and mature commercial deployments at the highest levels (Almeida et al., 2023). By applying the TRL framework, researchers and project developers can objectively categorize diverse technological solutions. The benchmark is utilized to identify engineering barriers to large scale implementation, and determine the exact interventions required to advance a concept from a localized pilot project to a market-ready technology (Fotis et al., 2022).


UNDERSTANDING TRL IN WASTE VALORIZATION

The Metric of Maturity

TRL measures a technology's progress from basic research to full commercial operation.

Lab Success vs. Industrial Reality

Scoring identifies the "Maturity Gap" where high-yield lab processes taca tenkoo-economic hurdies during upsealing.

Assessing Economic Viability

TRL scores help correlate technical performance with Net Present Value and capital expenditure risks.

TECHNOLOGY MATURITY RANKINGS

TRL 9: Anaerobic Digestion

The only fully mature, commercially established technology for high-moisture potato residues.

TRL 6–8: The Pilot Phase

Technologies like Pyrolysis and Bioethanol are technically successful but require external legislative support.

TRL 3–5: Emerging Frontiers

Biohydrogen and Gasification offer zero-carbon potential but face profound technical and biological hurdies.

Figure 4. Scoring Technology Readiness Level (TRL) to assess commercial viability.

The commercial viability of processing potato side-streams depends strictly on the Technology Readiness Level (TRL) of the selected technologies. Anaerobic digestion for biogas generation is a fully mature technology operating at TRL 9, supported by thousands of active industrial facilities globally (Almeida et al., 2023). Conversely, advanced integrated biorefinery models, specifically those coupling continuous biobutanol fermentation with simultaneous product extraction, remain situated between TRL 4 and TRL 6, requiring further pilot-scale validation (Hijosa-Valsero et al., 2018). Hydrothermal carbonization systems are currently crossing the commercial threshold, with several full-scale plants newly operational proving their technical reliability for wet organic matrices (Romano et al., 2023).

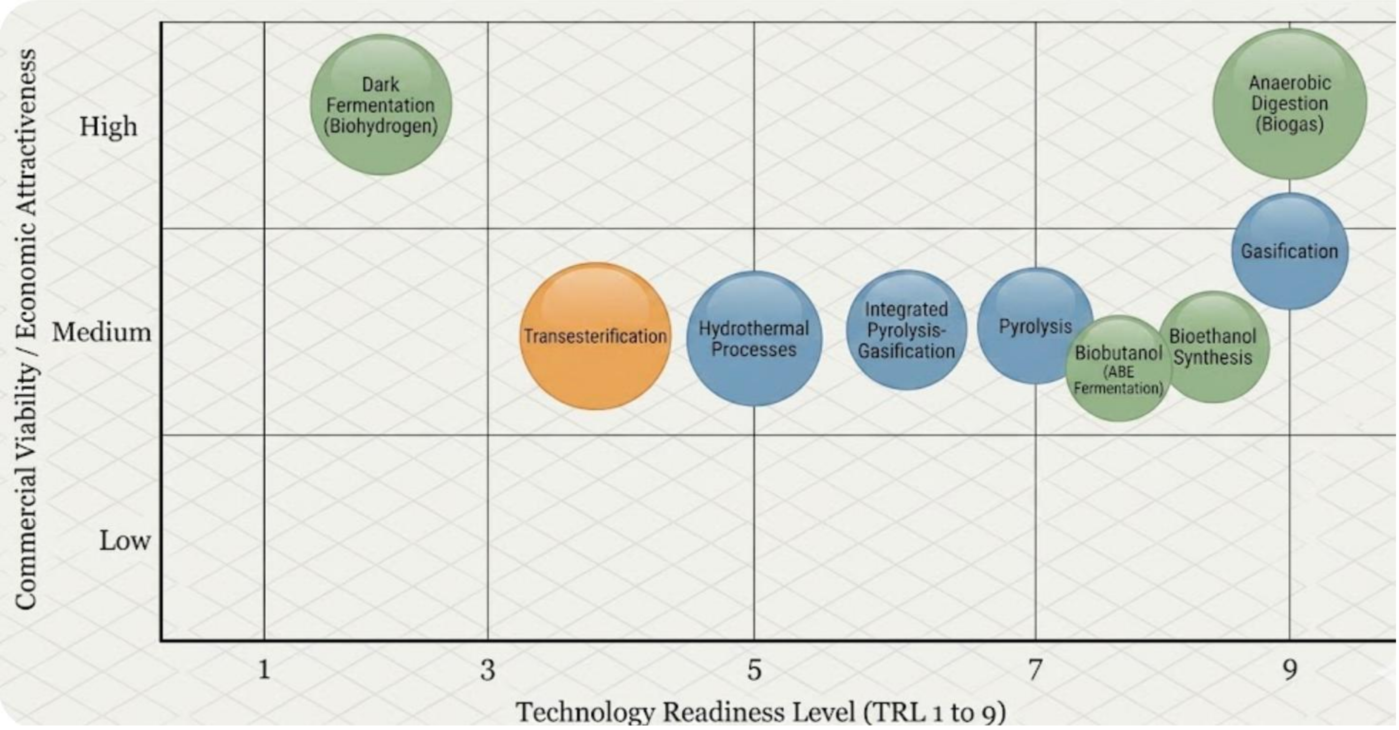


Figure 5. Synthesis: The Techno-Economic Assessment Matrix

Figure 5 above shows the Techno-Economic Assessment Matrix which is a visual analytical framework that evaluates various potato side-stream-to-energy conversion pathways by plotting them against two critical dimensions. The first dimension is their Technology Readiness Level (TRL) on the X-axis (ranging from 1 to 9) and the on the Y-axis represents their Commercial Viability / Economic Attractiveness (categorized as Low, Medium, and High).

This matrix effectively classifies which of the technologies are ready for immediate, profitable industrial deployment versus those that require further research and development. Based on the matrix, the technologies are classified as follows:

1. High Technology Readiness (TRL 9) & High Economic Attractiveness

- Anaerobic Digestion (Biogas): Biogas production technology proven to be the most optimal position on the matrix at TRL of 9 with High Commercial Viability. As discussed in the previous evaluations, it is a fully mature, globally established technology that efficiently converts high-moisture organic waste into renewable energy without requiring energy intensive drying processes.

2. High Technology Readiness (TRL 7–9) & Medium Economic Attractiveness

This category represents technologies that are well developed and commercially available but still face economic bottlenecks due to either high capital expenditures or high energy requirements during processing:

- Gasification (TRL 8–9): Highly mature thermal processes that only offer medium economic attractiveness. This is largely due to the massive thermodynamic penalty incurred when drying high-moisture feedstocks (like potato peels) before thermal conversion.

- Bioethanol and Biobutanol (ABE Fermentation) (TRL 7.5–8.5): These mature biochemical pathways are technically proven but remain at medium commercial viability. The economic limitations here are related to product toxicity and the high energy costs associated with distillation and downstream product separation.

- Pyrolysis (TRL 7): Similar to gasification, standalone dry pyrolysis is technologically advanced but economically constrained by potato side-stream drying requirements.

3. Medium Technology Readiness (TRL 4–6) & Medium Economic Attractiveness

These technologies in this third category are currently crossing the pilot-scale threshold into early commercialization. The technologies listed below also showing moderate profitability:

- Integrated Pyrolysis-Gasification (TRL 6): Combining thermal processes such as pyrolysis and gasification can maximize carbon recovery, but dual-reactor infrastructure keeps economic attractiveness at moderate level.

- Hydrothermal Processes (TRL 5): Both Hydrothermal carbonization and Hydrothermal liquefaction processes bypass the need for potato side-stream dehydration, making them highly suitable for wet biomass. Currently the technologies are still scaling up to a higher commercial maturity level.

- Transesterification (TRL 4): Utilizing potato peel-derived lipids or catalysts for biodiesel is promising technology but requires further validation to push beyond medium commercial viability.

4. Low Technology Readiness (TRL 2) & High Economic Attractiveness

- Dark Fermentation (Biohydrogen): Positioned uniquely on the matrix, this pathway sits at a very low TRL of 2 but boasts High Economic Attractiveness. Biohydrogen production technology is still confined largely to laboratory-scale research. Direct production of zero-carbon biohydrogen represents a highly lucrative future energy carrier if the current biological and technology scaling challenges can be neutralized.

In summary, the Techno-Economic Assessment Matrix demonstrates that while Anaerobic Digestion is the most reliable and profitable choice for immediate industrial application, emerging technologies like Dark Fermentation hold immense economic potential if advanced through the TRL scale. Meanwhile, mature thermal and alcoholic fermentation technologies require integrated biorefinery models to elevate their medium economic attractiveness into highly profitable ventures.

7.3 Energy Efficiency and Distillation Penalties

Evaluating the net thermodynamic output of these facilities requires a strict accounting of internal energy consumption. Technology Readiness Levels clearly show that standalone bioethanol and biobutanol plants suffer from high energy penalties during the distillation and purification stages. These final phases often consume a significant fraction of the gross energy recovered to separate the alcohols from the dilute fermentation broth (Soni et al., 2023). Dry thermal processing technologies incur massive latent heat deficits when processing high-moisture potato peels which render thermodynamically negative without prior mechanical dewatering (Almeida et al., 2023). Therefore, wet-pathway technologies, specifically anaerobic digestion and hydrothermal carbonization, maintain the highest net energy efficiencies by circumventing these thermal vaporization penalties entirely (Catenacci et al., 2022).

7.4 Economic Indicators and Profitability

Economic modeling indicates that standalone energy production from agricultural side streams often struggles to maintain profitability due to high capital expenditures and fluctuating energy market prices. However, shifting the operational architecture to a cascading biorefinery model positively improves financial viability. Techno-economic assessments confirm that integrated facilities designed to extract high-value polyphenols prior to energy conversion, followed by combined biogas and biochar production, yield Internal Rates of Return (IRR) exceeding 10% and significantly shortened payback periods (Almeida et al., 2023). Implementing such integrated systems in regions like Ostrobothnia, provides robust Net Present Values (NPV) by simultaneously reducing waste disposal costs and generating multiple revenue streams from energy and biochemical sales.

8. Advanced Refining and Standardization

8.1 Refining Pathways to Transport Fuels

Decarbonization initiatives of global transport sector require the replacement of fossil-based petrol, diesel, and aviation jet fuels with low-carbon liquid alternatives which are sustainable (Suckling et al., 2022). Currently basic biological fermentation yields simple alcohols like bioethanol, in addition, advanced processing is necessary to synthesize complex, drop-in hydrocarbon fuels that are compatible with existing heavy transport infrastructure.

Ordinary biogas generated from potato side-streams require extensive purification to meet the strict standards required for vehicle fuel or grid injection. The primary refining pathway involves the continuous removal of carbon dioxide and hydrogen sulfide through advanced scrubbing technologies. Utilizing cost-effective amine stripping systems constructed from fiberglass minimizes the initial capital costs while reliably elevating the methane concentration to grid-compliant biomethane specifications (Makkonen, 2025). Concurrently, liquid biofuels such as biodiesel synthesized from waste lipids must be standardized through rigorous catalytic treatment and distillation to strictly meet international fuel benchmarks, including the EN 14214 and ASTM D6751 standards (Valero et al., 2019).

Table 1. Summary of Upgrading Pathways

Technology / Pathway	**Initial Feedstock / Intermediary**	**Target Fuel Product**	**Feasibility & Efficiency Status**

Direct Dehydration & Blending	Fermentation broth (Bioethanol)	Gasohol (Gasoline substitute)	Commercially mature; requires extensive dehydration to <0.5% water content.
Direct Blending	ABE Fermentation (Biobutanol)	Diesel / Gasoline drop-in	High energy density and low hygroscopicity; proven compatibility with DI diesel engines (Rakopoulos et al., 2010; Ebrahimian et al., 2022).
Biological Methanol Synthesis	Biogas / Methane	Biomethanol	Emerging technology utilizing immobilized methanotrophs (Patel et al., 2021).
Steam Reforming	Biogas / Methane	Biomethanol	Technically feasible but reduces overall plant energy efficiency to ~32.3% due to high parasitic energy loads (Wu et al., 2023).
Fischer-Tropsch Synthesis	Syngas/ Biomethane	Synthetic Diesel & Jet Fuel	Capable of producing heavy transport fuels but suffers from severe thermodynamic penalties, yielding ~26.4% energy efficiency (Wu et al., 2023).

Feasibility evaluation of converting basic bio-alcohols or biomethane into synthetic ready drop-in fuels reveals a strict economic and thermodynamic trade-off. Upgrading processes demand highly expensive conversion technologies and incur severe energy penalties. For example, while standard anaerobic digestion coupled with biogas upgrading can achieve a net plant energy efficiency of 56.8%, introducing steam reforming to synthesize liquid bio-methanol drops the overall energy efficiency to 32.3% (Wu et al., 2023).

8.2 Optimization Benchmarks and Standards

The effective functioning of these conversion facilities is achieved through advanced computational analytics and process simulation. The Anaerobic Digestion Model No. 1 (ADM1) is useful for engineers to probabilistically simulate the degradation kinetics of complex agricultural substrates to establish highly accurate hydraulic retention times and organic loading rates prior to physical construction (Koch et al., 2020). Moreover, the machine learning algorithms and Design of Experiments (DoE) protocols provide dynamic real-time optimization of reactor parameters (e.g. pH and temperature) to ensure maximum thermodynamic yield while preventing acid-induced system failure (Pei et al., 2022). These digital standards act as benchmarks to provide a uniform structure for safely scaling waste-to-energy frameworks in agricultural sectors worldwide.

A unified framework of standards guides the bioenergy sector towards structural reliability. The VDI 4630 standard deals with substrate characterization and Biochemical Methane Potential (BMP) testing. This standard provides an essential foundation for establishing unified pricing mechanisms which allow operators to reliably select and evaluate feedstocks. Building upon this analytical baseline, VDI 4631 establishes the rigorous quality criteria required for the engineering design of biogas which is a vital technical benchmark for investors and operators evaluating the viability of new capital projects. In the global context, ISO 20675:2021 framework standardizes biogas terminology and classification. This creates a unified technical vocabulary, which ensures that technology can more easily make its way across borders, and the same goes for safety protocols.

Table 2. Optimization Benchmarks and Standards summary.

Standard / Benchmark	**Description and Application**

VDI 4630	Governs the characterization of organic substrates and establishes strict protocols for Biochemical Methane Potential (BMP) test. This allows reliable evaluation of feedstocks and unification of price setting strategies.
VDI 4631	Establishes the engineering quality criteria needed for the physical design of biogas plants. It is a key technical benchmark intended for investors and operators evaluating new project viability and operational excellence.
ISO 20675:2021	Global quality standard for biogas terminology, classification, and safety protocols. This framework provides the technical basis for transferring technology internationally and ensures uniform safety measures across borders.
EU BREF (Waste Treatment)	Describes the Best Available Techniques for waste treatment facilities. This standard mandates environmental and emission limits for industry sites to comply with EU regulations.
VFA/TA Ratio	The universal operational benchmark for measuring the ratio of Volatile Fatty Acids and Total Alkalinity. It enables continuous monitoring of facilities and proactive control of processes within bioreactors.

At the same time, Artificial Intelligence (AI) and machine learning algorithms are creating a new set of digital standards for biorefinery optimization. Using advanced data-driven approaches, it has become feasible to predict feedstock properties and volumetric gas yields successfully, making real-time decisions much easier in complex high-solids digestion systems (De Clercq et al., 2020; Wang et al., 2020).

Europe systematically moves toward its climate neutrality targets. The combination of sustainable food waste management including potato side-stream and advanced pre-treatment technologies will be indispensable. The integration of bioenergy infrastructure with other renewable conversion technologies will be essential for establishing a resilient and carbon-neutral energy future.

9. Conclusion

Waste-to-energy strategies are directly aligned with the physical and thermodynamic realities of the targeted feedstocks. Raw potato side streams contain up to 85 percent water. The use of traditional dry thermal processing technologies like gasification or dry pyrolysis creates huge thermodynamic deficits. These high-temperature methods demand extensive preliminary dehydration to vaporize the inherent moisture even before conversion begin. These methods severely compromise the net energy efficiency of the facility. For sustaining a positive energy balance and operational profitability, wet-pathway conversion technologies are prioritized.

Anaerobic digestion (AD) serves as the absolute best conversion technology in short term. Operating at a fully mature Technology Readiness Level (TRL) of 9, AD directly processes high-moisture biomass, allowing facilities to completely bypass expensive dehydration phases. This biological pathway is exceptionally well-suited for Finland’s transition toward decentralized renewable energy, specifically within the Ostrobothnia region. This approach perfectly matches Finland's national strategy to shift toward localized energy recovery from difficult agricultural residues.

Hydrothermal carbonization (HTC) is the most promising technological alternative in the medium term. Through the application of pressurized aqueous conditions at temperatures between 180 °C and 260 °C in HTC, water remains liquid, entirely avoiding the thermal vaporization penalty faced by other thermal processes. This reaction quickly produces a thick black hydrocarbon material that makes an excellent solid fuel or soil amendment. HTC is presently at a TRL of 5 to 6. This means that high capital costs of pressurized reactors limit its near-term deployment for smaller farms. The ongoing commercial scale-up will make it a very attractive and profitable option for future deployment.

Looking toward future potato side-stream to energy projects, the focus shift from specialized energy generation to multifunctional, integrated biorefineries. Financial returns are greatly improved through the sequential extraction of high-value polyphenols followed by energy conversion, and further linking biogas production to biochar production. Moreover, the new infrastructure must adhere to the digital standard with machine learning.

The use of Artificial Intelligence (AI) and machine learning is leading a new class of digital standards for biorefinery optimization. AI-enabled frameworks enable the prediction of feedstock properties and gas yields, allowing for real-time decision-making in complex conversion technologies. The adoption of sustainable feedstock management, advanced pre-treatment engineering, and the combination of bioenergy with other renewables will be needed for resilient climate action and carbon neutrality as Europe, including Finland, moves towards

10. References

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11. *Appendix*

Table 3: Potato side-stream to energy conversion technologies Comparison

Conversion Method	Moisture Tolerance	Heat Needed	Pretreatment Need	TRL	Key Products	Main Bottleneck	Suitability for Ostrobothnia
Anaerobic Digestion (AD)	High (Ideal for 79–85% moisture)	Low (Mesophilic ~37 °C or Thermophilic ~55 °C)	Yes (Mechanical or chemical comminution)	9	Biogas, Digestate	Long retention time, volatile fatty acid accumulation, and handling impurities	High: Strongly aligns with Ostrobothnia's farm-scale biomethane targets
Bioethanol Synthesis	High	Low (Fermentation) / High (Downstream distillation)	Yes (Intensive saccharification and hydrolysis)	6–8	Bioethanol	Product toxicity to microbes and massive energy penalties	Medium: Technically proven, but centralized, large-scale biorefineries are required
Biobutanol Fermentation	High	Low (Fermentation) / High (Downstream distillation)	Yes (Inhibitor removal and extensive hydrolysis)	6–8	Biobutanol	Severe microbial toxicity and high energy costs	Medium: Offers a superior drop-in fuel compared to ethanol,
Dark Fermentation for Biohydrogen	High	Low (Mesophilic to thermophilic)	Yes (Requires suppression of methanogens)	3–4	Biohydrogen	Biological instability, and low volumetric yields,	Low: Confined mostly to laboratory and pilot research
Pyrolysis	Low	High (300–700 °C)	Yes (Intensive drying and mechanical sizing)	7	Bio-oil, Biochar, Syngas	Immense thermodynamic penalty for drying wet waste	Low: Low economic margins due to necessary latent heat requirements.

Gasification	Low (Requires dry feedstock)	Very High (800–1200 °C)	Yes (Drying and pelletizing)	8–9	Syngas	Energy-intensive drying phase, and tar formation,	Low: Extremely capital-intensive
Integrated Pyrolysis and Gasification	Low	Very High	Yes (Intensive drying)	5–6	High-quality Syngas	Complex dual-reactor operational dynamics	Low: Dual-system architecture exacerbates the capital costs for small-scale projects.
Hydrothermal Carbonization (HTC)	High (Ideal for 15–25% dry matter)	Medium (180–260 °C under pressurized water)	Minimal (Utilizes the inherent moisture of the substrate)	5–6	Hydrochar, Aqueous liquid	High capital expenditures due to pressurized reactors	Medium: Highly promising, but high CAPEX currently limits small farm adoption.
Hydrothermal Liquefaction (HTL)	High	Medium-High (250–370 °C under high pressure)	Minimal	3–5	Biocrude / Bio-oil	Complex bio-oil upgrading required	Low-Medium: Excellent for wet biomass, but the resulting biocrude requires advanced catalytic upgrading
Transesterification	Low	Low to Medium	Yes (Requires strict lipid extraction and dehydration)	9	Biodiesel, Glycerol	Heavy reliance on lipid-rich feedstocks (oils/fats)	Low: Potato side-streams are starch-rich, not lipid-rich
Methanol Synthesis	Low	High (Reforming and Synthesis)	Yes (Extensive syngas/biogas cleaning and upgrading)	7–9	Biomethanol	Severe thermodynamic energy penalties	Medium: Upgrading raw biogas to methanol halves the overall net plant energy efficiency.