# Introduction

Potatoes are starchy crops that represent the world’s fourth most important crop. Valorization of potato wastes and particularly peels, would be an advantageous approach for transforming waste into valuable products, including chemicals, energy sources food ingredients. Such valorizations aim to reduce waste, enhance sustainability, and create economic value from what would otherwise be an obstacle to sustainability.

In this context, the present case study explores some of the potential production routes of starch, microbial fermentation to ethanol, and anaerobic digestion to biogas and compost.

# Define the general data system

Table 1 includes the initial information that must be defined in the software regarding plant production, capital cost calculations, and possible heat recovery systems. It should be noted that the facility's capacity was estimated to represent the amount of potato peel generated in Belgium in 2022.

Table 1. Definition of general system parameters

|  |  |  |
| --- | --- | --- |
|  | **Parameter** | **Value** |
| **Specific production** | Load type | Substrate |
| Main product / Substrate | Potato peel |
| Substrate load (t/y) | 560000 |
| **General CAPEX**  **parameters** | Operating hours (h/y) | 8000 |
| Year of Study | 2020 |
| Interest rate (-) | 0.05 |
| Detail level of linearization of CAPEX | Real |
| Indirect Cost Factor (-) | 1.44 |
| Direct Cost Factor (-) | 2.60 |
| **Heat pump parameters** | Heat pump switch | No |

# Define the chemicals compounds

Table 2 lists the compounds involved in the two proposed production routes, also providing heat capacity and molecular weight data when necessary.

Table 2. Compounds required for the production systems proposed (Part 1)

|  |  |  |
| --- | --- | --- |
| **Component** | **Heat capacity (kJ/kg·K)** | **Molecular weight (g/mol)** |
| Proteins | – | – |
| Lipids | – | – |
| Phenolics | – | – |
| Cellulose | – | – |

Table 3. Compounds required for the production systems proposed (Part 2)

|  |  |  |
| --- | --- | --- |
| **Component** | **Heat capacity (kJ/kg·K)** | **Molecular weight (g/mol)** |
| Proteins | – | – |
| Lipids | – | – |
| Phenolics | – | – |
| Cellulose | – | – |
| Hemicellulose | – | – |
| Lignin | – | – |
| Starch | – | – |
| Sugar | – | – |
| Ash | – | – |
| H2O | 4.18 | 18.01 |
| Enzymes | – | – |
| EtOH | 2.44 | 46.07 |
| CO2 | 0.84 | 44.01 |
| CH4 | 2.22 | 16.04 |
| O2 | 0.92 | 32.00 |
| N2 | 1.04 | 28.01 |
| Biogas | – | – |
| Compost | – | – |
| Biomass | – | – |

# Define the reactions

le 4 and 5 specify the mass balances of the syntheses that take place in the stoichiometric reaction units for the biogas and ethanol production routes, respectively.

Table . Reactions involved in anaerobic digestion and cogeneration

|  |  |
| --- | --- |
| **Reaction name** | **Reaction equation** |
| Cellulose DA | -1 Cellulose → 0.2 CH4 + 0.7 CO2 + 0.1 Biomass |
| Hemicellulose DA | -1 Hemicellulose → 0.15 CH4 + 0.75 CO2 + 0.1 Biomass |
| Lipids DA | -1 Lipids → 0.56 CH4 + 0.34 CO2 + 0.1 Biomass |
| Proteins DA | -1 Proteins → 0.33 CH4 + 0.57 CO2 + 0.1 Biomass |
| Starch DA | -1 Starch → 0.25 CH4 + 0.65 CO2 + 0.1 Biomass |
| CHP | -1 CH4 – 4 O2 → 2.75 CO2 + 2.25 H2O |

Table . Reactions involved in thermal-enzymatic hydrolysis and fermentation to produce ethanol

|  |  |
| --- | --- |
| **Reaction name** | **Reaction equation** |
| Cellulose hydrolysis | -1 Starch → 1 Sugar |
| Hemicellulose hydrolysis | -1 Hemicellulose → 1 Sugar |
| Starch hydrolysis | -1 Starch → 1 Sugar |
| Sugar fermentation | -1 Sugar → 0.1 Biomass + 0.5 EtOH + 0.4 CO2 |
| Cellulose fermentation | -1 Sugar → 0.1 Biomass + 0.3 EtOH + 0.6 CO2 |
| Hemicellulose fermentation | -1 Sugar → 0.1 Biomass + 0.4 EtOH + 0.5 CO2 |
| Starch fermentation | -1 Sugar → 0.1 Biomass + 0.5 EtOH + 0.4 CO2 |

# Define the utilities

Table shows the costs and CO2 emissions associated with the electricity or heat exchange utilities used in the processes, also including the typical temperature ranges for the latter case.

Table . Definition of system utilities

|  |  |  |  |
| --- | --- | --- | --- |
| **Utility**  **data** | **Parameter** | **Costs (€/MWh)** | **CO2 emissions (t/MWh)** |
| Electricity | 120 | 0.33 |
| Heat | – | 0.24 |
| Chilling | 35 | 0.10 |
| **Temperature data** | **Parameter** | **Temperature (ºC)** | **Costs (€/MWh)** |
| Superheated steam | 140 | 29 |
| High pressure steam | 110 | 29 |
| Medium pressure steam | 100 | 29 |
| Low pressure steam | 95 | 29 |
| Cooling water | 15 | 29 |

# Inputs information for the superstructure mapping

Table 7 to 10 provide the prices and composition fractions for each of the inputs *required* to produce starch, ethanol and biogas.

Table . Information to define Potato peel input

|  |  |  |
| --- | --- | --- |
| **Source name** | Potato peel | |
| **Cost input (€/t)** | -62 | |
| **Components** | **Component name** | **Composition fraction** |
| Proteins | 0,025 |
| Lipids | 0,002 |
| Phenolics | 0,020 |
| Cellulose | 0,011 |
| Hemicellulose | 0,007 |
| Lignin | 0,003 |
| Starch | 0,095 |
| Sugar | 0,003 |
| Ash | 0,035 |
| H2O | 0,800 |

Table . Information to define water input

|  |  |  |
| --- | --- | --- |
| **Source name** | Water | |
| **Cost input (€/t)** | 1.9 | |
| **Components** | **Component name** | **Composition fraction** |
| H2O | 1 |

Table . Information to define enzymes input

|  |  |  |
| --- | --- | --- |
| **Source name** | Enzymes | |
| **Cost input (€/t)** | 34 614 | |
| **Components** | **Component name** | **Composition fraction** |
| Enzymes | 1 |

Table . Information to define air input

|  |  |  |
| --- | --- | --- |
| **Source name** | Air | |
| **Cost input (€/t)** | 0 | |
| **Components** | **Component name** | **Composition fraction** |
| O2 | 0.21 |
| N2 | 0.79 |

It is worth mentioning that each input has been assigned a name that will be used to refer to them in the unit operations of the routes in which they are involved. Additionally, in **Error! Reference source not found.** a gate fee of 62 €/t of potato peel was applied, which represents the cost of avoiding waste incineration in Belgium.

# Outputs information for the superstructure mapping

Table 11 shows the sales prices of the main products obtained in the proposed production routes.

Table . Information to define the main products of the processes

|  |  |  |
| --- | --- | --- |
| **Product name** | **Price output Input (€/t)** | **Product Type** |
| Starch | 712 | Main product |
| Ethanol | 765 | Main product |
| Biogas | 430 | Main product |
| Compost | 15 | Main product |

# Pretreatment unit operations for the routes

Table includes the data necessary to configure the grinding pretreatment unit operation in the software.

Table . Definition of the grinding unit (Part 1)

|  |  |
| --- | --- |
| **Grinding** | |
| **General parameters** | |
| Parameters | Value |
| Temperature in (ºC) | 22 |
| Temperature out (ºC) | 25 |

Table 13. Definition of the grinding unit (Part 2)

|  |  |
| --- | --- |
| **Grinding** | |
| **Cost related parameters** | |
| Reference flow type | Entering mass flow |
| Reference flow (t/h) | 250 |
| Components | All components of the input streams |
| Reference cost (M€) | 0.263 |
| Reference Year | 2017 |
| Exponent | 0.60 |
| **Utility requirements – Electricity requirements** | |
| Reference flow type | Entering mass flow |
| Energy consumption (MWh/t) | 0.016 |
| Components | All components of the input streams |
| **Separation efficiency** | |
| Separation information | All components enter the next unit |

# Route from potato peel to starch

Table , 15 and 16 provide the data required to represent the two centrifugation and drying units that can be combined to achieve the production of starch, correspondingly.

Table . Definition of the centrifugation milk-pulp for starch production

|  |  |
| --- | --- |
| **Centrifugation milk – pulp** | |
| **General parameters** | |
| Parameters | Value |
| Temperature in (ºC) | 25 |
| Temperature out (ºC) | 25 |
| **Cost related parameters** | |
| Reference flow type | Entering mass flow |
| Reference flow (t/h) | 7.92 |
| Components | All components of the input streams |
| Reference cost (M€) | 0.2046 |
| Reference Year | 2007 |
| Exponent | 0.38 |
| **Utility requirements – Electricity requirements** | |
| Reference flow type | Entering mass flow |
| Energy consumption (MWh/t) | 0.0005 |
| Components | All components of the input streams |
| **Separation efficiency** | |
| Separation information | Solid stream with 20% of the water |
| Liquid stream with starch, cellulose, hemicellulose and lignin |

Table 5. Definition of the centrifugal sieving for starch production

|  |  |
| --- | --- |
| **Centrifugal – sieving** | |
| **General parameters** | |
| Parameters | Value |
| Temperature in (ºC) | 31.4 |
| Temperature out (ºC) | 31.4 |
| **Cost related parameters** | |
| Reference flow type | Entering mass flow |
| Reference flow (t/h) | 21.18 |
| Components | All components of the input streams |
| Reference cost (M€) | 0.0558 |
| Reference Year | 2007 |
| Exponent | 1.04 |
| **Utility requirements – Electricity requirements** | |
| Reference flow type | Entering mass flow |
| Energy consumption (MWh/t) | 0.001 |
| Components | Starch; H2O |
| **Separation efficiency** | |
| Separation information | Liquid stream with the main product |
| Solid stream with 10% liquid loss |

Table 6. Definition of the drying unit for starch production

|  |  |
| --- | --- |
| **Drying** | |
| **General parameters** | |
| Parameters | Value |
| Temperature in (ºC) | 45 |
| Temperature out (ºC) | 55 |
| **Cost related parameters** | |
| Reference flow type | Entering mass flow |
| Reference flow (t/h) | 0.635 |
| Components | All components of the input streams |
| Reference cost (M€) | 0.221 |
| Reference Year | 2007 |
| Exponent | 0.65 |
| **Heating Requirements** | |
| Reference flow type | Entering mass flow |
| Required Cooling / Heating (MWh/t) | 0.5854 |
| Components | Liquids of the input streams |
| **Separation efficiency** | |
| Separation information | Starch with 12% humidity as final product |

# Rute from potato peel to ethanol

Table 17 to 21 provide the data required to represent the hydrolysis, fermentation, centrifugation, distillation and dehydration units that can be combined to achieve the production of ethanol from potato peel, correspondingly.

Table . Definition of the thermal-hydrolysis unit for ethanol production

|  |  |  |  |
| --- | --- | --- | --- |
| **Thermal and enzymatic hydrolysis** | | | |
| **Inputs** | | | |
| Input | Enzymes | | |
| **General parameters** | | | |
| Parameters | Value | | |
| Temperature in (ºC) | 25 | | |
| Temperature out (ºC) | 80 | | |
| **Cost related parameters** | | | |
| Reference flow type | | Entering mass flow | |
| Reference flow (t/h) | | 0.10 | |
| Components | | All components of the input streams | |
| Reference cost (M€) | | 0.073 | |
| Reference Year | | 2006 | |
| Exponent | | 0.53 | |
| **Heating Requirements** | | | |
| Reference flow type | | Entering Flow Heat Capacity | |
| Required Cooling / Heating (∆T) | | 100 | |
| Components | | Liquids of the input streams | |
| **Mixing Coefficients** | | | |
| Mixing coefficient | | 0.002 | |
| Mixing Table: Reference flow 1 | | Reference Flow Type | Entering mass flow |
| Components | Enzymes |
| Mixing Table: Reference flow 2 | | Reference Flow Type | Entering mass flow |
| Components | Starch |
| **Reactions** | | | |
| Reaction name | | Conversion (%) | Reactant |
| Cellulose hydrolysis | | 70 | Cellulose |
| Hemicellulose hydrolysis | | 70 | Hemicellulose |
| Starch hydrolysis | | 90 | Starch |
| **Separation efficiency** | | | |
| Separation information | | All components enter the next unit | |

Table . Definition of the fermentation unit for ethanol production (Part 1)

|  |  |
| --- | --- |
| **Fermentation** | |
| **Input** | |
| Inputs | Water |

Table 19. Definition of the fermentation unit for ethanol production (Part 2)

|  |  |  |  |
| --- | --- | --- | --- |
| **Fermentation** | | | |
| **Cost related parameters** | | | |
| Reference flow type | | Entering mass flow | |
| Reference flow (t/h) | | 0.625 | |
| Components | | All components of the input streams | |
| Reference cost (M€) | | 0.186 | |
| Reference Year | | 2020 | |
| Exponent | | 0.719 | |
| **Utility requirements – Electricity requirements** | | | |
| Reference flow type | Entering mass flow | | |
| Energy consumption (MWh/t) | 0.00044 | | |
| Components | Liquids of the input streams | | |
| **Heating Requirements** | | | |
| Reference flow type | Entering Flow Heat Capacity | | |
| Required Cooling / Heating (∆T) | 10 | | |
| Components | Liquids of the input streams | | |
| **Reactions** | | | |
| Reaction name | Conversion (%) | | Reactant |
| Sugar fermentation | 99 | | Sugar |
| Cellulose fermentation | 10 | | Cellulose |
| Hemicellulose fermentation | 20 | | Hemicellulose |
| Starch fermentation | 30 | | Starch |
| **Separation efficiency** | | | |
| Separation information | Release of the CO2 produced  The remaining components all enter the next unit | | |

Table . Definition of the centrifugation unit for ethanol production (Part 1)

|  |  |
| --- | --- |
| **Centrifugation** | |
| **General parameters** | |
| Parameters | Value |
| Temperature in (ºC) | 35 |
| Temperature out (ºC) | 35 |
| **Cost related parameters** | |
| Reference flow type | Entering mass flow |
| Reference flow (t/h) | 7.92 |
| Components | Liquids of the input streams |
| Reference cost (M€) | 0.213 |
| Reference Year | 2006 |
| Exponent | 0.38 |
| **Utility requirements – Electricity requirements** | |
| Reference flow type | Entering mass flow |
| Energy consumption (MWh/t) | 0.01 |
| Components | Solids of the input streams |

Table 21. Definition of the centrifugation unit for ethanol production (Part 1)

|  |  |
| --- | --- |
| **Centrifugation** | |
| **Separation efficiency** | |
| Separation information | Liquid stream with the main product |
| Solid stream with 10% liquid loss |

Table . Definition of the distillation unit for ethanol production

|  |  |
| --- | --- |
| **Distillation** | |
| **General parameters** | |
| Parameters | Value |
| Temperature in (ºC) | 35 |
| Temperature out (ºC) | 82 |
| **Cost related parameters** | |
| Reference flow type | Entering mass flow |
| Reference flow (t/h) | 120 |
| Components | All components of the input streams |
| Reference cost (M€) | 0.60 |
| Reference Year | 2008 |
| Exponent | 0.60 |
| **Heating Requirements** | |
| Reference flow type | Entering mass flow |
| Required Cooling / Heating (MWh/t) | 0.41 |
| Components | All components of the input streams |
| **Separation efficiency** | |
| Separation information | EtOH 90% of mass purity in distillate (96% recovery) |

Table 23. Definition of the drying unit for ethanol production (Part 1)

|  |  |
| --- | --- |
| **Drying** | |
| **Inputs** | |
| Source names | Air |
| **General parameters** | |
| Parameters | Value |
| Temperature in (ºC) | 25 |
| Temperature out (ºC) | 55 |
| **Cost related parameters** | |
| Reference flow type | Entering mass flow |
| Reference flow (t/h) | 0.86 |
| Components | All components of the input streams |
| Reference cost (M€) | 0.271 |
| Reference Year | 2008 |
| Exponent | 0.60 |

Table 24. Definition of the drying unit for ethanol production (Part 2)

|  |  |  |
| --- | --- | --- |
| **Drying** | | |
| **Mixing Coefficients** | | |
| Mixing coefficient | 138.11 | |
| Mixing Table: Reference flow 1 | Reference Flow Type | Entering mass flow |
| Components | H2O; EtOH |
| Mixing Table: Reference flow 2 | Reference Flow Type | Entering mass flow |
| Components | O2; N2 |
| **Separation efficiency** | | |
| Separation information | EtOH with 1% impurities as final product | |

# Rute from potato peel to biogas

**Error! Reference source not found.**le 25 to 31 provide the data required to represent the anaerobic digestion, composting, bioupgrading or Combined Heat and Power (CHP) units that can be combined to achieve the production of compost, biogas or heat and power from potato peel, correspondingly.

Table . Definition of the anaerobic digestion unit for biogas / heat and power / compost production (Part 1)

|  |  |
| --- | --- |
| **Thermophilic anaerobic digestion** | |
| **General parameters** | |
| Parameters | Value |
| Temperature in (ºC) | 25 |
| Temperature out (ºC) | 55 |
| **Cost related parameters** | |
| Reference flow type | Entering mass flow |
| Reference flow (t/h) | 0.63 |
| Components | Solids of the input streams |
| Reference cost (M€) | 9 |
| Reference Year | 2006 |
| Exponent | 0.328 |
| **Utility requirements – Electricity requirements** | |
| Reference flow type | Entering mass flow |
| Energy consumption (MWh/t) | 0.01 |
| Components | All components of the input streams |
| **Heating Requirements** | |
| Reference flow type | Entering mass flow |
| Energy consumption (MWh/t) | 0.127 |
| Components | All components of the input streams |
| **Separation efficiency** | |
| Separation information | A first flow with CH4 and CO2 |
| A second flow with the solids and a 20% of liquid |

Table 26. Definition of the anaerobic digestion unit for biogas / heat and power / compost production (Part 2)

|  |  |  |
| --- | --- | --- |
| **Thermophilic anaerobic digestion** | | |
| **Mixing Coefficients** | | |
| Mixing coefficient | 0.10 | |
| Mixing Table: Reference flow 1 | Reference Flow Type | Entering mass flow |
| Components | All components of the peels |
| Mixing Table: Reference flow 2 | Reference Flow Type | Entering mass flow |
| Components | H2O |
| **Reactions** | | |
| Reaction name | Conversion (%) | Reactant |
| Cellulose DA | 100 | Cellulose |
| Hemicellulose DA | 100 | Hemicellulose |
| Lipids DA | 100 | Lipids |
| Proteins DA | 100 | Proteins |
| Starch DA | 100 | Starch |

Table 27. Definition of the composting unit for compost production

|  |  |  |
| --- | --- | --- |
| **Composting** | | |
| **General parameters** | | |
| Parameters | Value | |
| Temperature in (ºC) | 55 | |
| Temperature out (ºC) | 80 | |
| **Cost related parameters** | | |
| Reference flow type | Entering mass flow | |
| Reference flow (t/h) | 3.75 | |
| Components | Solids of the input streams | |
| Reference cost (M€) | 0.48 | |
| Reference Year | 2006 | |
| Exponent | 0.60 | |
| **Utility requirements – Electricity requirements** | | |
| Reference flow type | Entering mass flow | |
| Energy consumption (MWh/t) | 0.035 | |
| Components | Solids of the input streams | |
| **Reactions** | | |
| Product | Yield factor | Inert Chemicals |
| Compost | 0.715 | H2O |
| **Separation efficiency** | | |
| Separation information | Compost with a 5% humidity as final product | |

Table 28. Definition of the CHP unit for heat and power production (Part 1)

|  |  |
| --- | --- |
| **CHP** | |
| **Inputs** | |
| Source name | Air |

Table 29. Definition of the CHP unit for heat and power production (Part 2)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **CHP** | | | | |
| **General parameters** | | | | |
| Parameters | Value | | | |
| Temperature in (ºC) | 55 | | | |
| Temperature out (ºC) | 90 | | | |
| **Energy efficiency** | | | | |
| Energy Type | Combined Heat and Power | | | |
| Conversion Efficiency | Efficiency | | 0.35 | |
| Heat efficiency | | 0.50 | |
| **Cost related parameters** | | | | |
| Reference flow type | Entering mass flow | | | |
| Reference flow (t/h) | 5 | | | |
| Components | CH4 | | | |
| Reference cost (M€) | 0.001 | | | |
| Reference Year | 2021 | | | |
| Exponent | 1 | | | |
| **Utility requirements – Electricity requirements** | | | | |
| Reference flow type | | Entering mass flow | | |
| Energy consumption (MWh/t) | | 0.24 | | |
| Components | | O2; N2 | | |
| **Reactions** | | | | |
| Reaction name | | Conversion | | Reactant |
| CHP | | 100 | | CH4 |
| **Mixing Coefficients** | | | | |
| Mixing coefficient | | 6.51 | | |
| Mixing Table: Reference flow 1 | | Reference Flow Type | | Entering mass flow |
| Components | | O2; N2 |
| Mixing Table: Reference flow 2 | | Reference Flow Type | | Entering mass flow |
| Components | | CH4; CO2 |
| **Separation efficiency** | | | | |
| Separation information | | It is not necessary to define compound separation in this unit, although a warning message appears when completing the tabs | | |

Table . Definition of the bioupgrade unit for biogas production (Part 1)

|  |  |
| --- | --- |
| **Bioupgrade** | |
| **General parameters** | |
| Parameters | Value |
| Temperature in (ºC) | 55 |
| Temperature out (ºC) | 55 |
| **Utility requirements – Electricity requirements** | |
| Reference flow type | Entering mass flow |
| Energy consumption (MWh/t) | 0.2633 |
| Components | CH4; CO2 |

Table 31. Definition of the bioupgrade unit for biogas production (Part 2)

|  |  |
| --- | --- |
| **Bioupgrade** | |
| **Cost related parameters** | |
| Reference flow type | Entering mass flow |
| Reference flow (t/h) | 3.22 |
| Components | CH4; CO2 |
| Reference cost (M€) | 1.94 |
| Reference Year | 2006 |
| Exponent | 0.93 |
| **Separation efficiency** | |
| Separation information | CH4 97.5% of mass purity as final product |

# Explore superstructure’s mapping

Feel free to connect routes to reduce waste, explore possibilities of combining routes to produce multiple products, or modify/add inputs and units to the superstructure based on prior knowledge. Trying diverse types of simple optimization or calculating the impacts of LCA to perform multi-objective optimization is algo encouraged.