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Optimal energy concept for decarbonisation of sea-buckthorn processing plants

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Abstract.

The decarbonisation of the industrial sector is required to achieve the objectives defined within the European Climate and Energy framework, since industry accounts for 37% of the total global energy consumption and for a quarter of global energy system CO_2 emissions [1]. In this context, this work aims the decarbonisation of a sea-buckthorn processing plant using structural and operational optimisation for the analysis of proposed energy supply concepts based on the integration of renewable energy sources, energy conversion components and storage systems.

Different configurations are evaluated to select the concept that leads to a minimisation of the operating costs and a CO_2 emissions reduction of the industrial site with installation costs within the investment range defined and the minimum payback period. Thus, the selected decarbonisation concept is able to achieve a reduction of 25% in operation costs (OPEX) and 31% in CO_2 with an investment (CAPEX) of 288.7 T€ and a payback time of 5.8 years. Additionally, the developed methodology can be used for the analysis of decarbonisation concepts for other industrial processes by the integration of an adapted techno-economic definition of the components for each energy concept proposed.

Key words. Decarbonisation, industrial process, renewable energies, structural optimisation, operational optimisation.

1. Introduction

The European Union (EU) has set ambitious targets aimed at creating a more sustainable, secure, and affordable energy system. These objectives are outlined in the 2030 Climate and Energy framework [1]:

1) Reducing greenhouse gas (GHG) emissions by at least 40% below 1990 levels by 2030 and become carbon neutral by 2050.
2) Increasing renewable energy share to have at least 32% of EU's final energy consumption coming from renewable sources.
3) Improving energy efficiency at least 32.5% by 2030 as a key strategy for reducing energy consumption and GHG emissions.

To achieve these goals, the decarbonisation of the industrial sector plays a key role, since it accounts for 37% of the total global energy consumption and for a quarter of global energy system CO_2 emissions [2]. Thus, energy concepts based on the integration of renewable energies, minimising investment and operating costs, need to be analysed in order to select the optimal decarbonisation concept adapted to the industrial site [3][4].

In this work, an optimal energy supply system based on renewable sources and energy storage is defined for the decarbonization of the industrial production of sea buckthorn-based products. For that purpose, different energy concepts are analysed considering the structural and operational optimisation.

2. Methodology

For the definition of an optimal energy supply system based on renewable sources and energy storage to decarbonize the industrial production of sea buckthorn-based products, different energy-supply concepts have been analysed using a commercial optimisation tool (TOP-Energy) [5] and including in-house developed operational logic to define the interactions between the components of each concept studied. The results coming from the analysis of these concepts are compared with the selected reference case considering the energetic and ecological impact as well as their economic efficiency.

A. Description of the industrial process and reference cases

The current energy supply system of the industrial facility consists in a gas boiler, steam generator and a $55kW_p$-PV plant connected to the electrical grid. The heat supply uses steam at 120°C as working fluid, which is required in processes such as flash pasteurisation at 76°C and other thermal treatments at 90°C for controlling, eliminating, or reducing pathogens to acceptable levels. The electricity and heat demand for this process are depicted in Fig. 1 and Fig. 2.

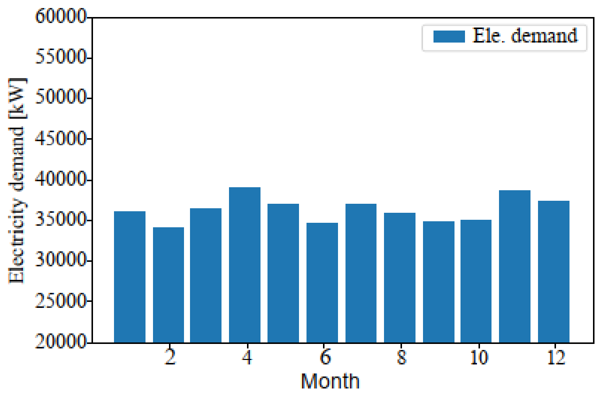

Fig. 1. Yearly electricity demand for operation with steam

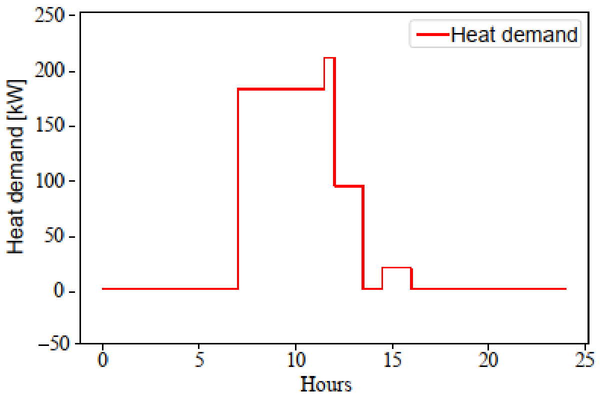

Fig. 2. Daily heat demand for operation with steam

As alternative heat working fluid, the utilisation of water at 95°C has also been analysed in order to evaluate the reduction of process heat demand, operation costs and CO_2 emissions.

B. Definition of decarbonisation energy concepts

In the definition of decarbonisation concepts, renewable energy sources, energy conversion components and energy storage should be included (Fig. 3). PV and solar thermal (ST) facilities use the available solar energy of the location to produce renewable electricity and heat, respectively. Additionally, energy conversion systems such as electric boiler (EB) and heat pumps (HP) are able to generate process heat from the incoming electricity. Thermal storage systems (TES) and batteries (BAT) allow a secure supply of the fluctuating renewable energy.

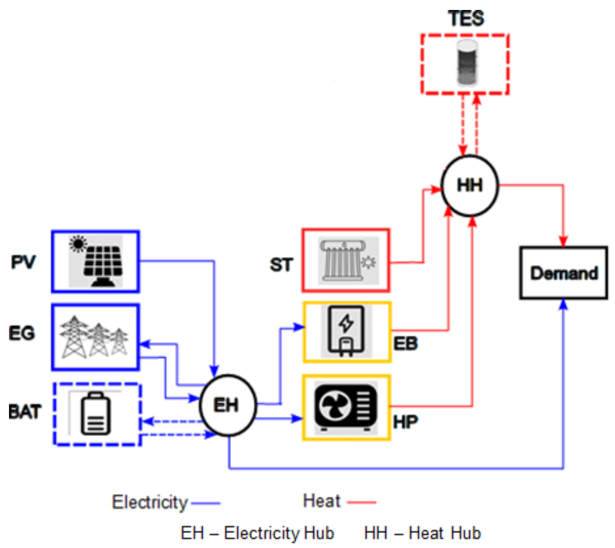

Fig. 3. Overview of decarbonisation energy concepts (adapted from [6])

C. Configurations analysed

The proposed configurations for the decarbonisation of the sea-buckthorn processing plant analyse the integration of PV plant, battery, electric boiler, heat pump, solar thermal plant and heat storage considering different components connections and heat sources for the heat pump.

- *Case 1.* All components for heat supply are connected to the process (HP, EB, ST, TES), using ambient air as HP heat source.
- *Case 2.* All components for heat supply are connected to the process (HP, EB, ST, TES), considering a geothermal heat source with a constant temperature of 32°C for the HP.
- *Case 3.* HP, EB and TES supply heat to the process and ST is used to charge the storage, considering ambient air as HP heat source.
- *Case 4.* HP and EB supply heat to the process, ST is used to charge the storage and TES is used as HP heat source.

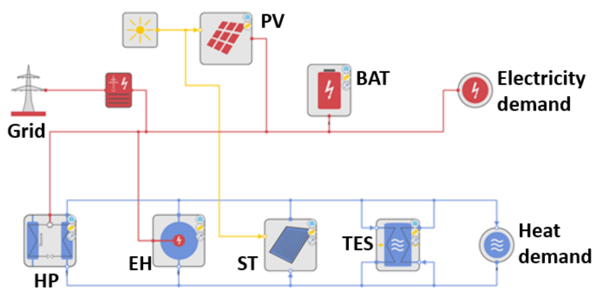

Fig. 4. Configuration of cases 1 and 2

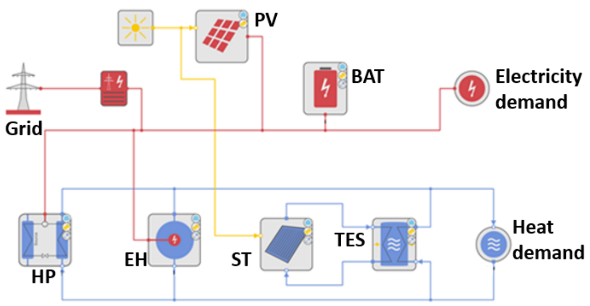

Fig. 5. Configuration of case 3

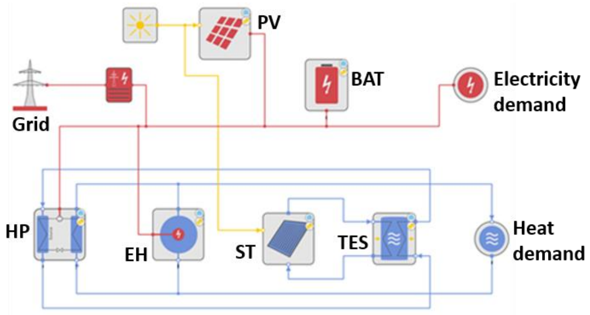

Fig. 6. Configuration of case 4

D. Modelling using structural optimisation

In structural optimisation, the operation of the energy system together with the size of system components are optimised. In this way, an appropriate dimensioning can support strategic decisions on an investment in a new energy concept. Thus, optimum values for renewable-energy (RE) systems and storages in stand-alone networks can be determined by structural optimization.

To that aim, minimum and maximum nominal capacities must be defined in the technical input data of the structural optimisation components. These determine the limits for dimensioning (see Table I).

Table I. - Dimensioning limits

COMPONENT PARAMETER	MINIMUM	MAXIMUM
PV-plant capacity (kW_p)	55	190
ST-plant surface (m^2)	0	75
Electrical heater (kW_{th})	0	250
Heat pump (kW_{th})	0	750
TES (kWh_{th})	0	500
Battery (kWh)	0	250

The specification of a positive minimum nominal capacity does not necessarily mean that the installation represented by the component is really integrated into the optimized system. This is only the case, when it is specifically defined in the model [5]. For the analysed concepts and considering the surface available in the industrial site, it is included for ST and PV plants with a maximum plant dimension of 75 m^2 and 190 kW_p, respectively.

E. CAPEX estimation and component definition

The estimation of the capital expenditure is based on a reference system: reference costs, area, energy gain and power ($\boldsymbol{CAPEX^0; A^0/Q^0/P^0_{nom}}$) and a scaling exponent γ:

$$\boldsymbol{CAPEX = CAPEX^0 \left(\frac{A/Q/P_{nom}}{A^0/Q^0/P^0_{nom}}\right)^{\gamma}} \quad (1)$$

The components have been evaluated using the following definitions:

- *Heat pump*

The calculation of the thermal output power for the heat pump, $\boldsymbol{P^{HP}_{out}}$, is based on its nominal capacity, $\boldsymbol{P^{HP}_{nom}}$, and part-load $\boldsymbol{\lambda^{HP}}$.

$$\boldsymbol{P^{HP}_{out} = P^{HP}_{nom} . \lambda^{HP}} \quad (2)$$

The coefficient of performance (COP) is calculated by:

$$\boldsymbol{COP^{HP} = 0.5 \frac{T^w_{out}}{T^w_{out} - T^c_{amb}}} \quad (3)$$

where: $\boldsymbol{T^w_{out}}$ is the outlet temperature of the heat sink, and $\boldsymbol{T^c_{amb}}$ corresponds to the ambient temperature of the heat source.

Thus, the output power can be evaluated by:

$$\boldsymbol{P^{HP}_{out} = P^{HP}_{in} . COP^{HP}} \quad (4)$$

with $\boldsymbol{P^{HP}_{in}}$ as the thermal input power.

- *Electric boiler*

For the electric boiler, the thermal output power $\boldsymbol{P^{EB}_{out}}$ is calculated considering the nominal capacity $\boldsymbol{P^{EB}_{nom}}$ and part-load $\boldsymbol{\lambda^{EB}}$:

$$\boldsymbol{P^{EB}_{out} = P^{EB}_{nom} . \lambda^{EB}} \quad (5)$$

The calculation of the EB output power is:

$$\boldsymbol{P^{EB}_{out} = P^{EB}_{in} . \eta^{EB}} \quad (6)$$

with an efficiency, $\boldsymbol{\eta^{EB}}$, of 0.95 and $\boldsymbol{P^{EB}_{in}}$ as input power.

- *Solar thermal facility*

The optical collector gain, $\boldsymbol{Q^0}$, is calculated using the global inclined incidence irradiance ($\boldsymbol{I}$), the nominal area of the solar thermal facility ($\boldsymbol{A^{ST}_{nom}}$) and assuming a collector efficiency ($\boldsymbol{\eta^0}$) of 0.84:

$$\boldsymbol{Q^0 = \eta^0 . I . A^{ST}_{nom}} \quad (7)$$

Thermal losses due to the temperature difference between average fluid temperature ($\boldsymbol{T_m}$) and ambient temperature ($\boldsymbol{T_{amb}}$) are considered by the losscoefficients, a_1 and a_2. Therefore, the collector loss Q^L is defined by:

$$Q^L = (a_1.(T_m - T_{amb}) - a_1.(T_m - T_{amb})^2).A_{nom}^{ST} \quad (8)$$

Therefore, the ST total heat output (Q^{ST}) is calculated using equation (9) considering the optical collector gain and losses:

$$Q^{ST} = Q^0 - Q^L \quad (9)$$

- *Thermal storage*

The energy balance for the thermal storage is defined by:

$$\frac{dE^{TES}}{dt} = \dot{Q}^{ch} - \dot{Q}^{dch} - \dot{Q}^{loss} \quad (10)$$

where: E is the stored energy at any time, $\dot{Q}^{ch}$ is the charging power:

$$\dot{Q}^{ch} = \eta^{ch}.P_{ch}^{TES} \quad (11)$$

with η^{ch} as charging efficiency and P_{ch}^{TES} as charging heat transfer rate, and $\dot{Q}^{dch}$ is the discharging power:

$$\dot{Q}^{dch} = \frac{1}{\eta^{dch}}.P_{dch}^{TES} \quad (12)$$

being η^{dch} the discharging efficiency and P_{dch}^{TES} the discharging heat transfer rate. The losses, $\dot{Q}^{loss}$, are calculated by (13) considering the relative losses (rel. loss):

$$\dot{Q}^{loss} = (rel.loss).E^{TES} - (1-\eta^{ch}).\dot{Q}^{ch} + (1-\eta^{dch}).\dot{Q}^{dch} \quad (13)$$

- *PV plant*

Optical collector gain (P_{out}^{PV}) calculation for the PV plant is calculated by:

$$P_{out}^{PV} = \eta^{PV}.P_{Peak}^{PV}\frac{I_g}{I_{STC}}.(1 + TC.(T_{cell}^{PV} - T_{STC}^{PV}) \quad (14)$$

where: P_{Peak}^{PV} is the peak power of whole PV; η^{PV} is the collector efficiency; I_{STC}, the incident radiation at standard test conditions (1000 W/m^2); TC, the temperature coefficient; T_{cell}^{PV}, temperature of the PV cell; T_{STC}^{PV} , the temperature at standard test conditions; and I_g , the global inclined incidence irradiance.

The peak power of the whole PV is defined by:

$$P_{Peak}^{PV} = P_{Peak}^{m^2}.A_{nom}^{PV} \quad (15)$$

with $P_{Peak}^{m^2}$ as the peak power per square meter. T_{cell}^{PV} is defined as follows:

$$T_{cell}^{PV} = T_{amb} + (I_g - I_{NOCT}).(T_{NOCT}^{cell} - T_{NOCT}^{amb}) \quad (16)$$

where: I_{NOCT} , is the solar radiation at which the Nominal Operating Cell Temperature (NOCT) is defined; T_{NOCT}^{cell} is the Nominal Operating Cell Temperature (318.15 k), and T_{NOCT}^{amb}, is the ambient temperature at which the Nominal Operating Cell Temperature (NOCT) is defined (298.15 k).

3. Results and discussion

Optimisation results are obtained considering two main objectives: minimisation of the operating costs and reduction of CO_2 emissions. These parameters are calculated using meteorological data of the plant site. The reference electricity price is 16.75 ct/kWh and selling price of the existing PV plant is 16 ct/kWh [7]. The maximum investment (CAPEX) defined for the concept implementation is 300 T€.

A. Selection of the reference case

In order to select the reference case to compare the analysed energy concepts, the evaluation of the two optimisation objectives is performed for the operation with steam at 120°C and with water at 95°C. Results from Table II show a 5% reduction of the operation costs and CO_2 emissions using water as working fluid, since it involves a 15% decrease of the process heat demand. Therefore, the selected reference case is the operation with water at 95°C.

Table II. – Results of the reference case

PARAMETER	STEAM	WATER
Operation costs (T€/year)	161	154
CO_2 emissions (t/a)	226	113

B. General system optimisation

- *Structural optimisation*

Table III shows the results obtained from the structural optimisation for the 4 cases evaluated. ST and PV are fixed in order to use the whole area available for installation of renewable energies at the industrial location.

In cases 1 and 2, all components involved in the heat generation and storage (HP, EB, ST and TES) can supply energy to the process. The structural optimisation shows the same capacities for both cases. Only the TES capacity increases in case 2 because of the consideration of a geothermal heat source for the HP with a constant temperature. In this case, the coefficient of performance (COP) is higher than in case 1, therefore the additional heat produced need to be stored.

Case 3 shows a process heat supply coming from the HP, EB and TES. In this case, the TES is charged by the ST plant. Therefore, a higher amount of heat demand is covered by the HP which leads to a greater capacity (155kW) and, consequently, the capacity of TES and EB decrease. In case 4, the TES is used as heat source of the HP. Thus, the EB covers a greater part of the heat demand and the HP capacity is lower than in the previous cases.

It is important to mention, that in all cases the structural optimisation does not include the battery integration in the optimal concept, since the benefits of selling surplus electricity are higher than the battery implementation because of its relative high CAPEX.

Table III. – Results from structural optimisation

COMPONENT SIZING	CASE 1	CASE 2	CASE 3	CASE 4
HP (kW)	140	140	155	70
EB (kW)	40	40	24	177
TES (kWh_{th})	150	158	130	145
BAT (kWh)	0	0	0	0
ST (m^2)	75	75	75	75
PV (kW_p)	190	190	190	190

- *Operational optimisation and investment*

According to the results collected in Table IV, the cases with a lower generation of CO_2 emissions are cases 1 and 2 with a reduction of 31% and 34%, respectively, considering the reference case with water as working fluid. The operation costs are 30% lower in case 2, but the integration of a HP with geothermal heat source requires a higher investment that almost achieves the maximum limit defined. Therefore, for this industrial site, it is selected the case 1 as energy supply concept with a payback time of 5.8 years.

It is also observed that, in case 4, the payback time is much higher than in the order cases because of the higher operation costs coming from the electricity costs required by the EB with a greater capacity.

Table IV. – Results from operational optimisation

PARAMETER	CASE 1	CASE 2	CASE 3	CASE 4
Operation costs (T€/year)	115	109	116	146
CO_2 emissions (t/year)	147	140	148	187
Investment (T€)	289	299	290	280
Payback time (year)	5.8	5.2	6	17.6

C. Sensitivity analysis

In order to analyse the influence of the electricity cost on the main components of the selected energy concept (case 1), a sensitivity analysis has been performed considering a price range between 20 ct/kWh and 250 ct/kWh. Fig. 7 shows that the optimised HP size should be between 120 kW and 170 kW for electricity prices between 16 ct/kWh and 150 ct/kWh, respectively. Higher electricity prices do not lead to higher HP capacities.

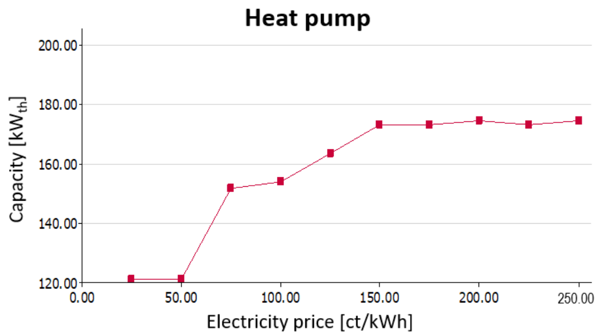

Fig. 7. HP sensitivity analysis

According to the results of the EB sensitivity analysis (Fig. 8), higher EB capacities are more profitable for lower electricity prices in comparison to the HP, since COP of HP is higher than the EB efficiency.

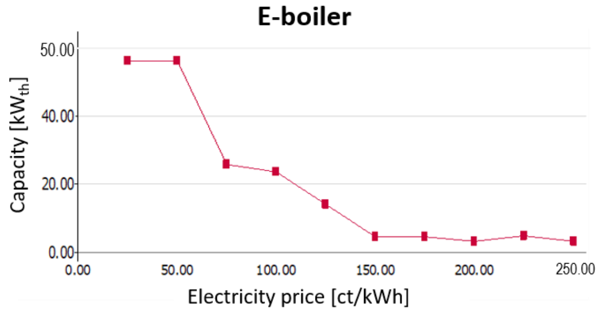

Fig. 8. EB sensitivity analysis

The sensitivity analysis of the battery explains the results obtained from the structural optimisation. The battery integration is profitable when the electricity price is higher than 100 ct/kWh due to its high investment costs.

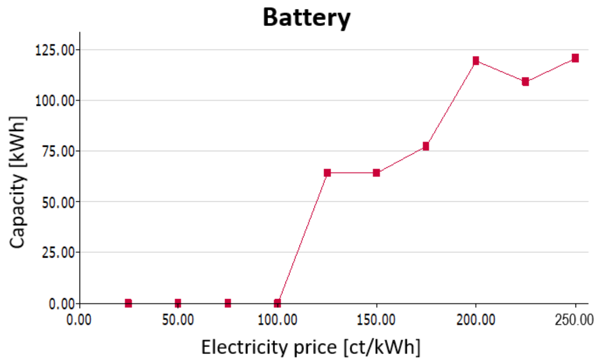

Fig. 9. Battery sensitivity analysis

4. Conclusions and future work

This work presents the analysis of different energy concepts for the decarbonisation of a sea-buckthorn processing plant using structural and operational optimisation. The proposed energy concepts are based on the integration of renewable energy sources (PV, ST), energy conversion components (EB, HP) and storage systems (BAT, TES).

The main conclusions of this analysis are:

1) The evaluation of the reference case with water as working fluid shows a 15% reduction of the heat demand that leads to a 5% reduction of operation costs and CO_2 emissions.
2) The most appropriate decarbonisation concept for the industrial site achieves a reduction of 25% in operation costs and 31% in CO_2 with an investment of 288.7 T€ and a payback time of 5.8 years.
3) The battery integration is not profitable for the considered electricity costs. The sensibility analysis of the selected configuration shows a profitable implementation for electricity prices higher than 100 ct/kWh.
4) A higher EB capacity is desirable in the energy concept when electricity prices are low. Otherwise, a higher HP capacity is required because of its higher COP in comparison to the EB efficiency.

The developed methodology can be used for the analysis of decarbonisation concepts for other industrial processes and locations by the integration of an adapted techno-economic definition of the components for each energy concept proposed.

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