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Sustainability of a Plastic Recycling/Symbiosis Network via Energy Quality Pinch Analysis

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The accumulation of plastic debris has been a consistently alarming global issue. Plastic recycling is a viable option, but the sustainability of the recycling network is directly linked with environmental performance, which is mainly dependent on energy consumption. This work aims to provide a sustainability assessment tool by determining the ideal minimum energy requirements for a circular system, with the main driven constraint to be the thermodynamic Energy Quality Factor (exergy fraction within the energy flow). The energy quality represents the extractible energy fraction from either a material or an energy stream. The Energy Quality Pinch Analysis serves as an assessment tool for a symbiosis network, as an indication of the existing system performance from the perspective of energy. The analysis considers cascades of the energy requirements released by recycling or symbiosis processes, evaluating the minimal external energy flows: high-quality energy input and waste energy output. The method is applied for a plastic waste recycling network case study, where the energy products can be reused or recycled for various recycling pathways. The case study shows that the maximum recyclable energy is 28 %. However, if the exergy destruction rate is taken into account for fuel conversion processes, the energy quality of the sources or sinks could be reduced. Various renewable fuels with different energy quality factors can be incorporated into the system tool to evaluate the energy requirements for the plastic system.

1. Introduction

Global production and manufacturing industries can make various adjustments to the workflows for the provision of goods or services to achieve Circular Economy and the Sustainable Development Goals. However, the involved processes are mainly driven by energy consumption, which plays an important factor in the sustainability of the production and recycling processes. In this case, energy recycling (recovery and reuse) in a circular system provides an indirect linkage to the circularity performance of a system.

Energy recycling is mainly limited by the energy quality of the stream. One typical example is the temperature of a heat flow, where temperature serves as the main thermodynamic criterion for heat recycling. This has been the core concept for Heat Integration developed by Linnhoff et al. (1994). Comprehensive reviews on the use of Pinch Analysis for Heat Integration can be found in (Klemeš et al., 2018). However, it is crucial to extend the energy recycling scope to heterogeneous energy-containing streams, including heat, material flows, and various sources of energy consumption processes (transportation, operation units, etc.). In this case, the suitable choice of an energy quality indicator that covers all types of scenarios would be an exergy-based indicator (Zheng and Hou, 2009), as it indicates the useful energy that is extractible from the energy streams and follows the cascading flow of energy from high to low-quality level.

The earliest idea of combining exergy and Heat Integration was to target the shaft work requirement or generation taking place during heat recovery (Dhole and Linnhoff, 1992). The approach is based on a diagram, plotting the system operations in the dimensions of the Carnot Factor (η_c) vs enthalpy (H), where η_c represents the energy quality of the cold and hot streams. Feng and Zhu (1997) later introduced the Ω-*H* diagram for representing the entire process system. The quality (Ω) is calculated by the ratio of exergy flow to energy flow. This formulation allows investigation of the potential improvement of exergy loss by lifting the Cold Exergy

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Composite Curve upwards. Yushkova and Lebedev (2019) have reasoned that replacing the enthalpy with exergy in a conventional T-H diagram could assess the recoverable exergy of the process while also determining the minimum exergy losses for a unit and even processes. The mentioned studies are limited to process systems with heat transfer. What is still missing is an extension of Exergy Pinch Analysis to regional symbiosis systems integrating heterogeneous process operations.

The plastic waste issue is a consistent threat worldwide and has considerably increased, especially during the COVID-19 pandemic periods (Klemeš et al., 2020). This underlines the importance of a sustainability assessment for plastic recycling networks. Chin et al. (2022) have proposed the use of Machine Learning with a Pinch-based approach to form a cascade recycling of plastic waste, but the sustainability assessment of the full network was not in the paper scope. Huysman et al. (2017) studied the compatibility between polymers and derived a sustainability indicator based on the overall exergy values for recycling processes. Various plastic recycling planning studies can be found in the literature. As one example – Brouwer et al. (2020) provided a general guideline for plastic waste categorisation but did not provide a guideline sustainability measurement for a plastic waste supply chain.

Many publications have highlighted the importance of plastic recycling, but a critical gap exists in the overall sustainability assessment of plastic waste recycling networks. This work aims to fulfil this research gap by proposing an Energy Quality Pinch concept to evaluate the ideal minimum energy requirements of a plastic recycling system. The available energy sources output from the system could fulfil some energy demands of the supply chain itself, but not all due to the limitation of the energy quality fraction. This work proposes the idea of energy recycling in the plastic recycling network with the Pinch concept.

2. Energy Quality Pinch Concept

The energy quality indicator used in this study draws an analogy to the exergy quality factor (Ω) as presented by Feng and Zhu (1997). The main difference is that they define it for process units heat recovery, while this study extends the definition to evaluate the quality of energy streams for heterogeneous systems, ranging from process-level to the scale of sites and regional networks.

Some energy outputs can represent secondary products whose energy is assumed to be extractable (e.g. power, secondary fuels and chemicals). The energy outputs can be considered as the energy sources, for which the energy quality is represented by the exergy value – see Eq(1). The exergy from a heat source depends on its temperature and can be calculated based on Eq(2). The exergy values for fuel can be regarded as the chemical exergy of the fuel components (Sayin Kul and Kahraman, 2016) – see Eq(3), which are dependent on the lower heating value (LHV). The chemical quality factor φ from Eq.3 also relies on the hydrogen-to-carbon ratio for the specific fuel – see Eq(4). Note that the chemical quality factor can be higher than 1, which signifies that power potential is more than the heat content of a fuel (Sayin Kul and Kahraman, 2016), where H, C, O and a represents the mass fractions of H, C, O and S atoms in a fuel.

$$Ex_{total} = Ex_{physical} + Ex_{chemical} \quad (1)$$

$$Ex_{physical} = Q\left(1 - \frac{T_0}{T}\right) \; where \; T \; in \; K \quad (2)$$

$$Ex_{chemical} = LHV\varphi \quad (3)$$

$$\varphi = 1.01401 + 0.1728\left(\frac{H}{C}\right) + 0.0432\left(\frac{O}{C}\right) + 0.2169\left(\frac{a}{C}\right)\left(1 - 2.20628\left(\frac{H}{C}\right)\right) \quad (4)$$

It is important to note that the modelled energy output is assumed to have not reached the consumer markets yet. If the boundary system is extended to the consumer site or used as a raw material for secondary production, the output can be assumed to be fully utilised and not regarded as a reusable energy source.

The exergy of a product is the useful energy that can be potentially recovered as work or power when it is brought into equilibrium with the reference environment (T_o, P_o, Z_o). The energy input follows the same logic but in the opposite manner, where the input is assumed to be extracted from a reference environment (T_o, P_o, Z_o) to the system. The energy quality of an energy stream 'i' (Zheng and Hou, 2009) can then be evaluated based on the ratio of total exergy flow to the total extractable energy- Eq(5).

$$Energy\ Quality_i = \frac{Ex_i}{En_i} \quad (5)$$

The energy consumption of a system plays the main role as it is directly related to environmental and economic performance, and its reduction contributes to a sustainable Circular Economy. It is important to minimise the net energy consumption of the system, but energy recycling can be constrained by the quality of the energy. This problem is analogous to the Heat Integration problem as discussed in (Linnholf et al., 1994), in which the main

objective is to reuse as much energy as possible to minimise external utilities, and the heat energy is mainly constrained by temperature. Since there are various energy forms within a circular system (heat, electricity and chemical), a unifying indicator is necessary to represent the energy quality.
In this work, the output product streams from the system boundary are termed as the Energy Supply/Source, while the input streams to the system boundary are denoted as the Energy Demand/Sink. As the energy quality follows a 'top-to-bottom' pattern (higher quality energy supply can serve demands with the same or lower quality) – similar to temperature, a cascading model for the energy streams can be formulated, suitable for applying the Pinch Analysis concept. Figure 1(a) shows the demonstration of the Energy Quality Composite Curves, which is inspired by the Total Site profile for a steam utility system. The Y-axis contains the energy quality factor instead of shifted temperature, while the X-axis contains the total energy values (not just enthalpy but includes various energy forms). This cascading pattern of energy flow can be represented clearer using the Energy Quality Grand Composite Curve – Figure 1(b), which shows the direction of the energy use.

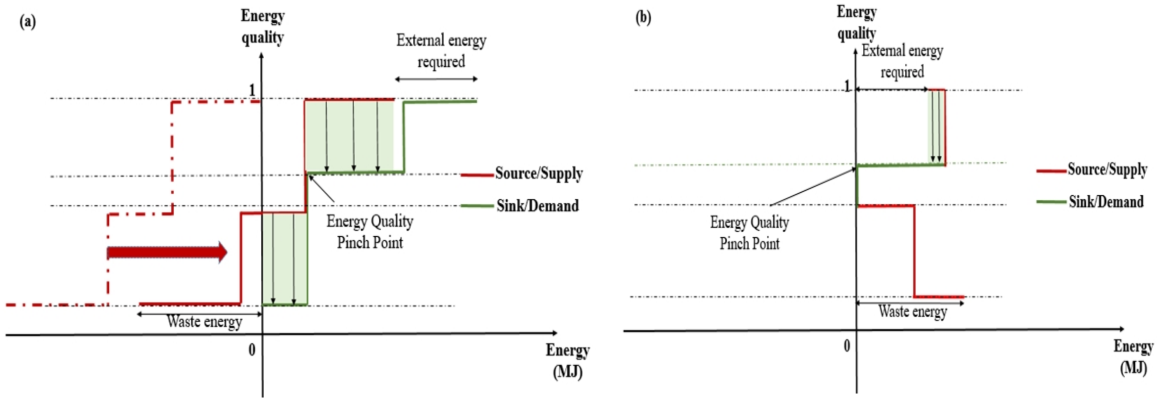

Figure 1: (a) Shifting the Source Composite Curve until it touches the Sink Composite Curve (b) Grand Composite Curve shifting from the original position

Table 1: Data used for the plastic waste recycling study

Inputs	Process	Outputs	Heat/Power required	Waste input[f] (t/y)	Conversion ratio[f] (t or kWh/t of input)
	Waste transport	-	Energy usage: 12.5 kWh/(t km)[a], total distance travelled = 2,000 km (Diesel vehicles)		
PE	Thermal recycling[b]	Gasoline	0.259 MWh/t; 0.018 t/t (diesel)	904.28	0.299 t/t
PE	Thermal recycling[b]	Diesel	0.259 MWh/t; 0.018 t/t (diesel)	3,037.94	0.068 t/t
PE	Thermal recycling[b]	Heavy oil	0.259 MWh/t; 0.018 t/t (diesel)	868,516.47	0.068 t/t
HDPE	Pyrolysis[c]	N-olefins	3.36 MWh/t 4.18 MWh/t (Thermal)	2,942.65	0.446 t/t
HDPE	Pyrolysis[c]	N-paraffins	3.36 MWh/t 4.18 MWh/t (Thermal)	3,136.48	0.432 t/t
PP	Pyrolysis[c]	Branch paraffins	3.36 MWh/t 4.18 MWh/t (Thermal)	3,038.08	0.333 t/t
PE	Incineration[b]	Heat	0.089 MWh/t	2,436.95	19.44 kWh/t
PP/PE/PET	Nanotubes 140[d]	Nanotubes	Sorting + Smashing: 0.438 MWh/t	3,038.13	0.15 t/t
PE	Nanotubes 160[d]	Nanotubes	Sorting + Smashing: 0.438 MWh/t	3,037.98	0.415 t/t
PE/PP	Nanotubes 252[d]	Nanotubes	Sorting + Smashing: 0.438 MWh/t	3,038.04	0.672 t/t
PE/PS/PP	Material recycling[d]	Pellets	Sorting + Smashing: 0.438 MWh/t	3,037.99	0.299 t/t
Others	Landfill[e]	-		15,000	-

[a](Fan et al., 2019), [b](Hur et al,. 2013). [c](Panepitto and Zanetti, 2021), [d](Bazargan and McKay, 2012), [e]Assuming only waste transportation to landfill with no additional outputs, [f](Santibanez-Aguilar et al., 2013)

3. Application to plastic recycling pathways

Plastic recycling is the solution for solving plastic waste accumulation, but it is also crucial to evaluate the sustainability of various possible pathways. A case study for a plastic recycling network, in which the data is mainly extracted from plastic portions of the municipal solid waste study in Mexico (Santibanez-Aguilar et al., 2013), is used to showcase the sustainability evaluation framework with Energy Quality Pinch Concept.

Table 1 shows the data used in this study. It consists of the existing plastic recycling pathways with their respective outputs and conversion ratios. The heat and power requirements are also provided. Note that the data is extracted with annual waste input and product production. The total distance travelled for waste transportation is estimated to be 2,000 km. Various processes require thermal input to run the operations. In this work, it is assumed that the fuel inputs for the processes are diesel unless stated otherwise, while transportation operations are assumed to use diesel fuel too. The heat released by incineration is assumed to be converted to a hot stream (steam) at 600 °C. Various properties of some selected fuels are presented in Table 2. The energy quality of fuels can exceed 1 due to the fact that the exergy is higher than the energy content, and according to Dincer and Rosen (2013), the partial pressure of CO_2 is accounted for when chemical exergy is calculated.

Figure 2 shows the Energy Quality Composite Curve for the plastic recycling system. It shows that the total energy sinks (demands) to be fulfilled exceed the energy sources several-fold. This is mainly due to the energy demand to transport all the waste to the processing facilities. The energy outputs from the processes are probably just enough to fulfil the demands. If waste transportation is neglected, the energy demands are still in abundance. The demands are mainly for high energy quality in pyrolysis processes (Figure 3). Shifting the Source Composite Curve to the right shows that the Pinch Point is at the energy quality of 1. It indicates ideally, at least about 209 MW of external energy is required for the plastics recycling network, while the unused energy is about 78 MW. About 28 % of energy can be recovered through the network with current qualities (Figure 3).

Table 2: Properties of some selected fuels. Data for diesel, bioethanol and biodiesel are from Sayin Kul and Kahraman (2016), while the LHV can be found from Engineering ToolBox (2003) and quality factor from Gong and Wall (2016)

Fuels	LHV (MJ/kg)	C (amu)	H (amu)	O (amu)	S (amu)	Energy quality
Diesel	43.14	85.29	13.64	0	1.07	1.06
Bioethanol	28.4	52	13	35	0	1.11
Biodiesel	38.59	12.13	77.06	10.81	0	2.18
Heavy oil	39	-	-	-	-	1
Natural gas	47.4	-	-	-	-	1.03
Coal	29	-	-	-	-	1.06
Fuelwood (20 % Humidity)	15	-	-	-	-	1.13
Sunlight	-	-	-	-	-	0.93
Hot steam (600 °C)	-	-	-	-	-	0.6

As measures to further reduce the external energy requirements, other fuels with higher energy quality sources can be used to cover the demands, such as bioethanol and biodiesel, based on Table 2. However, they have lower LHV values as compared to Natural Gas or diesel, which indicates a higher mass flow of fuels are required for the processes. The energy quality for energy demands or sinks can also be reduced by relying on lower quality fuels such as coal or wood. However, in this case, a higher amount of fuel is required for the process, which indicates more extraction from the environment.

Note that the exergy destruction is not considered in the analysis considering practical fuel conversion processes. If this is considered, the energy quality of sources and sinks will reduce with different ranges. Considering the exergy destruction rate for diesel fuel conversion is about 50 % (Sayin Kul and Kahraman, 2016), the sources' and sinks' energy quality can be reduced depending on the destruction rate (Figure 4), and the source/sink segments can be adjusted vertically. The analysis tool is flexible to account for various factors for energy and exergy flow.

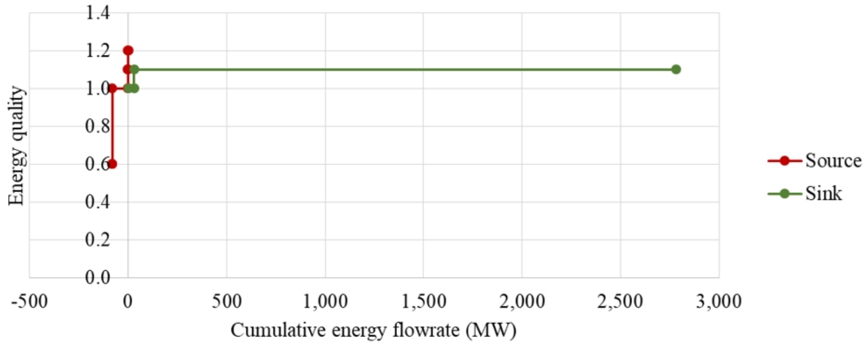

Figure 2: Energy Quality Composite Curves for plastic recycling network considering waste transportation

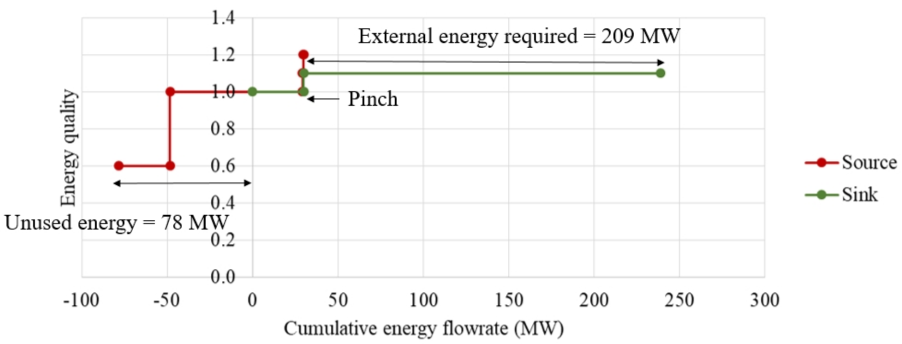

Figure 3: Shifted Energy Quality Composite Curves for plastic recycling network without waste transportation

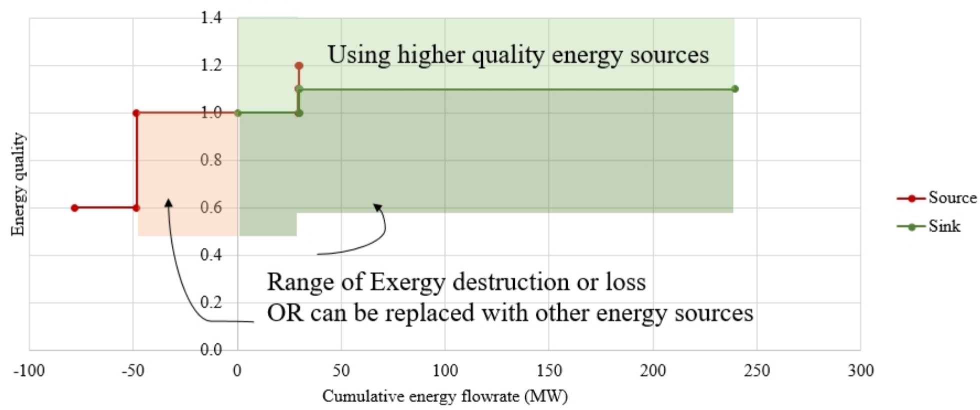

Figure 4: Shifted Energy Quality Composite Curves for plastic recycling network, shaded region indicates the possible vertical shifting of the source and sink segments

4. Conclusions

This work demonstrates the use of the Energy Quality Pinch concept to evaluate the sustainability of a plastic recycling network. The main thermodynamic constraint is set to be the energy quality, which indicates the fraction of exergy contained in the streams (energy or material). By setting proper boundaries on the system, the ideal minimum energy requirement for the system can be identified. Based on the selected case study, plastic waste transportation shows the most significant demand and the available sources are not enough to cover the overall demands. Only about 28 % of energy demands can be covered by removing the transportation factor. However, reducing the energy quality requirements for the sinks or increasing the energy quality of the sources could potentially reduce the system energy requirements, but it could induce more fuel requirements which means more extraction from the environment. The overall energy requirements, including the fuel production process, is to be studied. Note that also for fuel to power conversion has exergy destruction, and in this case, not full 100 % of the chemical exergy of the fuels can be used. Based on certain destruction rates, the Energy Quality Pinch Analysis could incorporate the source or sinks quality adjustment ranges for better assessment. Future work should consider a more detailed exergy analysis for the fuel conversion process.

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