

Article

# Potential Analysis of the Plastics Value Chain for Enhanced Recycling Rates: A Case Study in Iceland

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**Abstract:** In light of the circular economy gaining momentum, plastics recycling is regarded as a key solution to keep materials in the loop. Continuous efforts are needed to achieve the packaging waste recycling targets set by the European Union. Hence, this work evaluates the potential of the Icelandic plastics value chain for enhanced recycling rates. In addition to identifying the main challenges and opportunities, a feasibility study was conducted on the expansion of the deposit-return system to Skyr cups, allowing for closed-loop solutions. Based on the status quo, proposals for the improvement of the current waste and recycling system are made. Insights were acquired by semi-structured interviews with nine key stakeholders in Iceland, representing vital groups that influence the plastics value chain. The obtained answers followed the same trend, pointing out that a circular economy within the boundaries of Iceland is currently not feasible. This is mainly due to the strong dependence on international partners in all parts of the value chain except waste collection. However, major improvements are required to enhance the current waste collection rate of 28%. No conclusive evidence was found to justify the suitability of Skyr cups for the deposit-return system, as the disadvantages outweigh theoretically higher collection and recycling rates. Moreover, the extended producer responsibility scheme implemented with the Icelandic Recycling Fund is a valuable tool to enforce a design for recycling of products, enabling higher recycling rates. Despite one recycler operating in Iceland, Icelandic stakeholders consider sorting and treatment of mixed plastic waste as economically more efficient by collaborating with experts throughout Europe. Therefore, they expect that the current practice of exporting the majority of the domestic waste will prevail. On the contrary, the authors propose a comprehensive waste treatment and recycling scheme within Iceland, which requires a sorting step prior to three possible pathways, being (1) mechanical recycling, (2) alternative fuel, and (3) waste-to-energy. The aim of the proposed scheme is a reduction in greenhouse gas impact of plastics entering the waste stage by an efficient and flexible design of the relevant technologies within Iceland.

**Keywords:** plastics recycling; Iceland; deposit system; plastics value chain; CO<sub>2</sub> emission reduction



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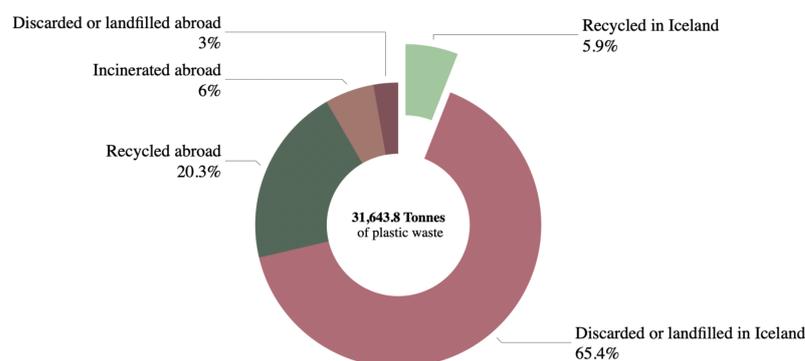
## 1. Introduction and Scope

The growing global environmental awareness both at a social and legislative level enabled the circular economy (CE) to gain momentum [1,2]. Unlike a linear economy based on the 'take-make-dispose' principle [3], a CE allows to reduce plastics waste, lower greenhouse gas emissions and preserve vital resources [4,5]. In order to close the loop for plastics, effective and efficient recycling of plastics waste is required, which demands an overall improvement throughout the plastics value chain [6]. Only if certain specifications for demanding applications can be met, virgin materials can be replaced by recycled [7]. As of now, closed-loop recycling accounts only for a small percentage of the total recycling being practised [8]. The most widely acknowledged examples are bottle-to-bottle

polyethylene terephthalate (PET) solutions, which are often characterized by homogeneous waste streams provided by separate collection schemes, such as deposit return systems (DRS) [9,10]. To develop a comprehensive circular plastics economy, continuous work and research is needed.

Although the shift to a CE is of global concern, this case study focuses on plastics recycling in Iceland, which offers an interesting view on this issue due to some unique features of the country. The island Iceland has an isolated high-income economy which strongly relies on the import of products due to limited means of domestic production and a small population size [11]. In the past, plastics waste was mainly disposed in landfills or ended up in the environment, which led to pollution and marine littering [12,13]. Hence, the long-term stability of mismanaged plastics is a threat to nature preservation [14,15]. Moreover, these problems are now directly affecting Iceland as its gross domestic product (GDP) is largely composed of fishery and tourism. IN total, 85% of Iceland's primary energy supply is provided by geothermal energy, wind energy, and hydropower, which is the highest share of renewable energy in any nation's total energy budget [16]. These renewable energy sources are potentially influencing the pricing of recyclates, which is mainly determined by the costs of waste collection and treatment [17]. By reducing the costs of these energy-intensive steps in a sustainable manner, recyclates could be economically more competitive compared to virgin materials [18].

The Icelandic left-green government addressed these issues by introducing an 18-step action plan in 2018, targeting plastic use and waste treatment [19]. More specifically, these steps include the ban of single-use items, such as grocery bags; and the reduction in use of plastics in the economy and in governmental facilities. Overall, measures to raise awareness for proper disposal of plastics were defined to prevent littering and pollution, increasing recycling efforts, and the recovery of plastics that have leaked into the environment. Moreover, the City of Reykjavik Climate Action Plan for 2021–2025 aims for a zero-waste policy by 'circular thinking' and the efficient use of resources [20]. This clearly indicates that the Icelandic government is willing to implement laws and regulations within the legal framework provided by the European Union, since Iceland is part of the European Economic Area (EEA). Core elements of the European directives on plastics are the defined recycling rates for plastic packaging of 50% by the end of 2025 and 55% by the end of 2030, respectively [21]. A study conducted by Desjardins [22] has shown that the recycling rate of plastics in Iceland in 2019 was at around 26% (see Figure 1), necessitating major improvements within the next few years.



**Figure 1.** Fate of plastics waste in Iceland in 2019 [22].

Still, landfilling is the most common fate of plastic waste, as roughly two-thirds of the waste are neither recycled nor incinerated. In addition to that, statistics clearly show that Iceland mostly exports plastic waste for further treatment, while only 2000 tons out of around 32,000 tons are recycled domestically. Icelandic waste is treated abroad by a variety of experts, mainly located in the Netherlands and Sweden, but also in Germany, Poland, and the UK [23]. The recycling process which is conducted at these facilities can be summarized according to Ragaert et al. [24] in (1) separating and sorting of the waste,

(2) baling for transport, (3) washing to remove contaminants, (4) grinding from products to flakes, and (5) re-granulating.

The recycling rate is the ultimate result of all previous parts of the plastics value chain and is heavily influenced by product design, service life, collection rate, and sorting rate [6]. Therefore, this work aims to evaluate the entire Icelandic plastic value chain to capture the status quo and to identify both challenges and opportunities for the improvement of recycling of domestic waste. This includes: (1) plastic production and manufacturing, (2) waste collection, and (3) waste treatment. Other than that, a feasibility study is conducted into whether or not the Icelandic deposit system can be expanded to other products allowing for closed-loop solutions. Due to a large domestic dairy industry, Skyr (Icelandic dairy product) cups were specifically selected in this case study. Finally, proposals for an improved Icelandic waste and recycling system are made on properly based scientific knowledge. This work is based on insights acquired by semi-structured interviews with key stakeholders in Iceland, as well as on a profound literature review. We emphasize that the methodology of this research is limited to qualitative data and that the feasibility of the proposed improvements must be evaluated by those responsible for the waste and environmental sector in Iceland.

## 2. Methodology

Within a one-month period in September 2021, a short-term scientific mission (STSM) was conducted in Reykjavik, Iceland. The STSM was carried out on behalf of the European Cooperation in Science and Technology (COST), which is funded by the Horizon 2020 Framework Programme of the European Union [25]. In particular, the performed work is allocated to COST Action 17133, aiming for circularity solutions by interconnecting researchers to tackle arising challenges in urban societies. The COST Action itself was divided into five working groups (WG), being (1) built environment, (2) sustainable urban water utilization, (3) resource recovery, (4) urban farming, and (5) transformation tools [26]. The presented work mainly contributes to WG 3, as it aspires to increase the recovery rate of plastic feedstock. Yet, plastic recycling has an impact on all other working groups, as it is fundamental in preserving Iceland's relatively untouched nature which is exposed to contamination due to littering and wrongful disposal. Microplastic resulting from polymer degradation pollutes groundwater and re-enters the food chain in agriculture and marine life (WG 2 and WG 4) [27,28]. Recyclates are commonly used in building and construction and can, therefore, be regarded as a resource for WG 1. Finally, recycling is only feasible if substantial public awareness is raised, which is why transformation tools from WG 5 are key to knowledge dissemination in order to increase public engagement [29].

Knowledge and insights were acquired by semi-structured interviews. Therefore, key stakeholders representing vital groups that influence the plastics value chain (researchers, politicians, companies, and governmental institutions) were identified. Interviewees were carefully selected based on their professional and academic background. Therefore, a good representation of the general recycling situation can be obtained due to the high quality of interviewees even at a small number of conducted interviews. Potential interviewees were contacted either by e-mail or phone and they were provided with a brief outline of the aim of the STSM and the interview questions. It is worth noting that the population size of only 360,000 diminished the potential interviewees, and that the group of politicians was highly underrepresented, since general elections were underway at the time of the STSM. Thus, the availability of politicians for interviews was hardly given.

Semi-structured interviews constitute versatile means of data acquisition, which is considered to suit the rather short research period of the STSM best [30]. Moreover, complex matters require less structured formats, leaving plenty of room for follow-up questions. In general, the interviewer prepares a set of predetermined questions with a clear idea of which topics should be covered. The conversation is then able to adjust according to the knowledge and interests of the individual interviewee [31]. The output of semi-structured interviews is of qualitative rather than of quantitative nature, meaning that

predominantly opinions of the individual interviewees are collected instead of numbers and data [32]. In this work, all stakeholders were interviewed using an interview guide (see Appendix A), ensuring that essential topics were covered in all interviews. However, the questionnaire was specifically expanded and adapted to the various fields of knowledge of each interviewee, yielding high-quality answers. Five interviews were held online and four were held in person, resulting in a total of nine interviews (see Table 1).

**Table 1.** Demographics of interviewees participating in this study.

| Interviewee | Gender | Nationality | Stakeholder Group |
|-------------|--------|-------------|-------------------|
| I1          | male   | Icelandic   | Waste management  |
| I2          | male   | Icelandic   | Waste management  |
| I3          | female | Icelandic   | Waste management  |
| I4          | female | Icelandic   | Politician        |
| I5          | male   | Icelandic   | Gov. institution  |
| I6          | male   | Icelandic   | Researcher        |
| I7          | female | Icelandic   | Researcher        |
| I8          | male   | Icelandic   | Recycling company |
| I9          | male   | Icelandic   | Mfg. company      |

It is worth noting that an expert's opinion could be biased, impacting the framework's reliability. Therefore, special attention was paid to minimize bias throughout the research process especially by framing objective interview questions. Furthermore, the questionnaire and the obtained answers were discussed among the authors to avoid researcher bias. Interviews in person tended to be longer as the interviewee seemed more talkative. The duration of the interviews ranged from 40 min to 2 h, and all interviews were audio recorded for subsequent verbatim transcription to facilitate information processing.

### 3. Evaluation of the Icelandic Plastics Value Chain

The public perception of plastics in Iceland was found to be predominantly negative, especially that of the older generation. Plastics is mostly generalized and little differentiation in plastic types and applications is made by the Icelandic society. As a result, the perception of the alleged disadvantages of plastics outweighs the environmental benefits achieved by replacing paper, wood, or glass. Pre-washing of waste prior to disposal and waste separation at different household bins or drop-off centers reportedly caused frustration among citizens, who expect technology to carry out these tasks for them. Nevertheless, the discussion on plastics in Iceland is gaining momentum, as the visibility of plastics' negative impacts on the environment by wrongful handling is clearly given. As a consequence, the awareness of the average person is changing, leading to more participation in the set-up waste collection schemes. Therefore, the waste management companies receive more plastics in their sorting streams than ever before.

This section is divided into the three main fields of research along the value chain. All aspects of the feasibility study on the expansion of the deposit system to Skeyr cups are included in the corresponding section of the plastics value chain. Since the obtained answers followed the same trend irrespective of the various stakeholder groups, no further distinction between the interviewees is made.

#### 3.1. Plastic Production and Manufacturing

Iceland does currently not feature domestic production of virgin resins and only a few small-scale plastic converters are operating. Therefore, the interviewees associated with the plastic sector were all located downstream the value chain. Throughout all interviews, a lack of regulations on what is allowed to enter the market was identified as a major obstacle for improved recycling rates. Currently, the recyclability of a product is often queued behind it being cheap and appealing, which can effectively only be changed by either consumer behavior or laws and regulations. Recyclability is defined as the

ability of a product to be collected, sorted, reprocessed, and ultimately reused. There is a cascading discrepancy between theoretical, technical, and apparent recyclability, urging a high theoretical recyclability in the first place as it limits the plastics recycling rate [33].

Interviewees highlighted the necessity of a design for recycling, which is extensively described in literature [34,35]. Thus, e.g., multi-material packaging shall be replaced by alternative solutions in an environmentally friendly manner and a practical disassembly of components shall be assured. Moreover, a reduction in plastic types and additives available should be forced according to the interviewees. Together with proper labelling, this would facilitate sorting both at waste management companies and in households.

A key player in regulating the products that enter the market and thus the Icelandic plastics cycle is the Icelandic Recycling Fund *Úrvinnslusjóður*, the extended producer responsibility (EPR) scheme. The collected fee is used to subsidize end-of-life treatment of plastics which includes waste collection and waste treatment. This incentive is required as the costs of waste collection and treatment exceed the value of (sorted) waste. More than 150 key stakeholders from across the packaging value chain made a statement in 2021 that the implementation of EPR is essential to waste management [36]. Without it, recycling would not be meaningfully scaled, resulting in continuous leaking of plastics to the environment at large scale. Given the fact that Iceland introduced an EPR scheme back in 2003, this is now well established and has the potential to have a lasting effect on recycling. According to EU directive 2018/851, the collected fee should cover the expenses of separate collection, treatment, and data gathering [37]. Moreover, a significant fee modulation shall be implemented, allowing to take the end-of-life performance into account. Therefore, the fee for a certain product shall be determined by its durability, reusability, dismantlability, and recyclability. As interviewees pledged, a notable economic impact would promote a better product design to enhance recycling. Currently, the Icelandic Recycling Fund charges only according to the amount of plastics introduced to the market, which is why measures are expected to be taken quickly.

Skyr is sold in Iceland mainly under two brand names: Ísey and KEA. Both are filled in Iceland's largest dairy MS [38]. The cups used by Ísey are made of polystyrene and are covered with a plastic sleeve. The product is protected by both an aluminum plate and a PET lid. Furthermore, a cardboard spoon is added for convenience, as it is offered for sale in many tourist places. The cup is produced by the Austrian company Greiner Packaging [39]. KEA mainly uses cups made of polypropylene with a cardboard wrap, which are closed with an aluminum plate and PVC lid. The cup is manufactured by the Icelandic plastics processing company Bergplast [40]. Both brands should be subject to the deposit system expansion, however, significant homogenization is required for a successful implementation. Ideally, a reduction to only one type of polymer for the cup should be achieved. Moreover, the dismantlability must be ensured for both labeling strategies.

### 3.2. Waste Collection

Waste collection in Iceland is carried out according to two coexisting systems. On the one hand, waste collection is set up by municipalities in the form of curbside collection, drop-off centers, and recycling centers. On the other hand, Iceland has established a deposit-return system (DRS) *Endurvinnslan* for various ready-to-drink beverages. Both systems are financed by the Icelandic Recycling Fund (IRF) *Úrvinnslusjóður*, which is an extended producer responsibility (EPR) scheme that collects a fee for every plastic product that is produced or imported. It was found that a large inhomogeneity in municipality-controlled waste collection schemes prevails throughout Iceland, as the various companies owned by municipalities pursue different strategies regarding waste collection. As a result, the overall collection rate of plastics is only 28%, with the rest being either discarded or sent to landfill. Although some of the operators are predominately collecting agriculture film, others are focused on waste collection from businesses and households. Businesses are mainly provided with large containers, often not intended for separate collection, which makes them hardly suitable for recycling. Households are equipped with a general waste

bin and a mandatory paper bin, but a separate recycling bin for plastics is only optional. Deficits in the collection rate of plastics can be exemplified by waste collection schemes in the Greater Reykjavik Area, which inhabits 60% of Iceland’s population. Only 30% of all homes are equipped with plastic recycling bins by the City of Reykjavik, revealing untapped potential to enhance collection rates. It has to be noted that drop-off and recycling centers provide accessible alternatives for plastic waste disposal.

Compared to the efficiency of waste collection by municipalities, the DRS yields significantly higher collection rates. *Endurvinnslan* was founded in 1989, making it the first of its kind at a nation-wide scale for a wide range of beverage containers [41]. The system was meant to both preserve the environment and increase packaging recycling rates. Thus, all ready-to-drink beverages, wine, and liquor with the exception of fresh milk products and juice extract are collected, even if they are not intact. By doing so, potential leakage of damaged containers to the environment is prevented. The deposit is currently set to ISK 18 for aluminum, PET bottles, and glass containers, which are collected in 60 return facilities throughout Iceland. The DRS yields high turnover and recycling rates of 86% in aluminum, 85% in PET, and 83% in glass, demonstrating that the Icelandic society is willing to participate [42]. Higher rates are prevented due to increasing numbers of tourists, who are not familiar with the system. With a three times higher collection rate for PET bottles compared to the overall collection rate of plastics, the deposit system bears the potential to set up efficient collection schemes for plastics beyond PET bottles, which is the framework for the case study conducted in this paper.

The feasibility study on a deposit system expansion to other plastic products obtained varying opinions among the interviewees. In this regard, first general requirements for a product to be successfully implemented into the Icelandic DRS for the purpose of recycling are outlined. Subsequently, the results obtained from the interviews on the feasibility study for Skyr cups are presented and discussed.

Products that are intended for the Icelandic DRS system shall be:

- Theoretically and practically recyclable;
- A defined unit which can be quantified by reverse vending machines;
- Available in a sufficient quantity to ensure economic viability;
- Pre-washed to minimize the levels of contaminants and smell;
- Of interest for potential buyers/recyclers.

Furthermore, it shall be ensured that all products of a certain category are included to prevent advantages in pricing for companies not participating in the DRS. Derived from the general requirements and the interviewee responses, the suitability of Skyr cups for the deposit system was assessed. The advantages and disadvantages of such an implementation are summarized in Table 2. Adding Skyr cups to the Icelandic DRS would offer the benefits to generate a homogeneous waste fraction, which would, therefore, significantly increase in value due to its overall good recyclability. Instead of paying a gate fee which is required for exporting mixed waste for sorting, the collected Skyr cups could be sold directly to recyclers. The interviewees pointed out that if Skyr cups are established in the deposit system, high return rates comparable to those of PET bottles could be achieved, which would be significantly higher than in the current collection scheme.

**Table 2.** Advantages and disadvantages for adding Skyr cups to the deposit system.

| Advantages                          | Disadvantages  |
|-------------------------------------|--|
| Well sorted plastics waste fraction | A lot of effort is needed for implementation                           |
| Increased value                     | Participation of society is questionable                               |
| High collection rate achievable     | Smell of open-container dairy products                                 |
| Good recyclability                  | Barcode is needed for counting   |
|                                     | Unification in resin type and design hardly achievable among producers |

However, the implementation is also linked to a number of disadvantages. Great effort is needed to align *Endurvinnslan*, manufacturers, and the public for a joint DRS expansion. The variety of Skyr cup solutions (e.g., plastic with direct-print label; plastic with paper label) and resin types used are considered to be the main challenges, necessitating unification among Skyr products on the market to guarantee a feasible collection in the deposit system. Moreover, the smell of dairy products, which remains in the cups to some extent, even after pre-washing, is expected to be problematic, which is why open-container dairy products are hardly suitable for longer storage and collection phases. In addition to that, the main supplier of dairy products was reported to be unwilling to release its products for the deposit system. This could not be verified as they were not available for an interview. However, their current product portfolio features an increasing amount of carton packaging (e.g., Tetra Pak), which requires no payment to the IRF. It is, therefore, likely that their efforts to generate efficient waste collection and recycling schemes for their products are limited.

### 3.3. Waste Treatment

As the data acquired by Desjardins [22] show, 65.4% of all plastic waste is discarded or landfilled in Iceland. Thus, the majority of the waste is not subject to any means of treatment. In contrast, the collected plastics fraction is commonly baled and, subsequently, sent abroad mostly to Sweden and the Netherlands. Only one company in Iceland conducts manual sorting prior to shipping with up to six persons working at a conveyor belt. They mostly identify hard plastics and sort them out of the stream. The receiving waste treatment plants are designed for large quantities of plastic waste by using advanced sorting technology. Therefore, proper sorting for either recycling, incineration, or landfilling can be provided. For most exported waste a gate fee is required, which is determined based on the fate of the waste. Consequently, the gate fee is lowest for shipments containing the largest quantity of recyclable waste. The Icelandic Recycling Fund then reimburses the waste management companies for their expenses. Export regulations for (hazardous) waste may affect shipments in the future even within the EEA. However, due to a greater import than export, empty space in cargo ships can be used for the export of plastic waste in a cost-effective manner.

Against common practice of exporting domestic waste, one recycling company operates in Iceland: *Pure North Recycling*. Their approach is similar to established mechanical recycling processes, but shows some significant differences and advantages. The main differences are that the power supply is covered by geothermal energy, and that hot steam and hot air are used for washing and subsequent drying of plastic flakes. Since their foundation in 2015, the recycling process was continuously developed and since 2020, they are able to generate profit by producing up to 2000 tons of recyclates annually. The demand for their recyclates is covered by an international plastics manufacturer, who converts the Icelandic materials abroad. *Pure North Recycling* is mostly focused on agriculture film, but also on hard plastics, such as pipes, buckets, and pallets. A key component in achieving a high quality of recyclates is their clean income stream of domestic plastic waste, which is set up by direct collaborations with companies. However, they are accused of cherry-picking the waste in a non-sustainable manner which enables them to make profit but decreases the value of the remaining waste.

Different opinions on the construction of a domestic sorting plant for an increased value of the collected waste prior to shipping were obtained. Although some interviewees were convinced that this would enhance recycling rates in a joint effort, enabling improved recycling both in Iceland and abroad, others were concerned about the economics and would prefer current practices of sending the waste abroad to larger sorting and recycling facilities. It can be concluded that an extensive cost-benefit evaluation would clarify on this behalf.

If the currently available Skyr cups were collected in the DRS, further sorting, e.g., swim-sink, NIR) between PP and PS must be conducted in order to prepare them for further

treatment. The removal of all extra material must be considered, especially for aluminum lids. Current practice of *Endurvinnslan* provides that the collected waste is treated at large facilities abroad which are operating 24/7. In the case of PET bottles out of the DRS in Iceland, the annually collected amount in Iceland requires 18 h to be processed at a typical sized recycling plant. Therefore, it is conceivable that Skyr cups are treated similarly.

#### 4. Summary and Conclusions

Currently, a circular economy within the boundaries of Iceland is not feasible, as most of the plastics production, manufacturing, and waste treatment is determined by international partners. Nevertheless, Icelandic stakeholders along the value chain have the opportunity to pave the way towards a more sustainable plastics economy, as national decisions and practices impact the overall recycling performance. Recommendations obtained from the experts’ opinions to enhance plastics recycling by improvements throughout the value chain are depicted in Figure 2. Despite most of the plastic products being imported and, therefore, little direct influence on plastics production and manufacturing, the extended producer responsibility scheme implemented with the Icelandic Recycling Fund is a valuable tool to enforce a design for recycling of these products. The incentive for a shift away from a non-recyclable product design should be given by the meaningfully-scaled taxation on imported plastics according to their end-of-life performance. By enhancing the theoretical recyclability, the actual recycling rate in Iceland can be increased.

|  <b>Plastics Production &amp; Manufacturing</b> |  <b>Waste Collection</b> |  <b>Waste Treatment</b> |
|---|--|---|
| <b>Incentive for the design for recycling of products should be given by the EPR scheme</b>                                       | <b>Harmonization of waste collection systems to improve the overall waste collection rate</b>              | <b>Domestic recycling should be pursued for homogeneous waste by using sustainable resources</b>            |
| <b>Icelandic Recycling Fund: Taxation according to end-of-life performance</b>  | <b>Mandatory recycling bin to enhance plastics recovery from households</b>                                | <b>Best results are achieved by collaborations with experts throughout Europe</b>                           |

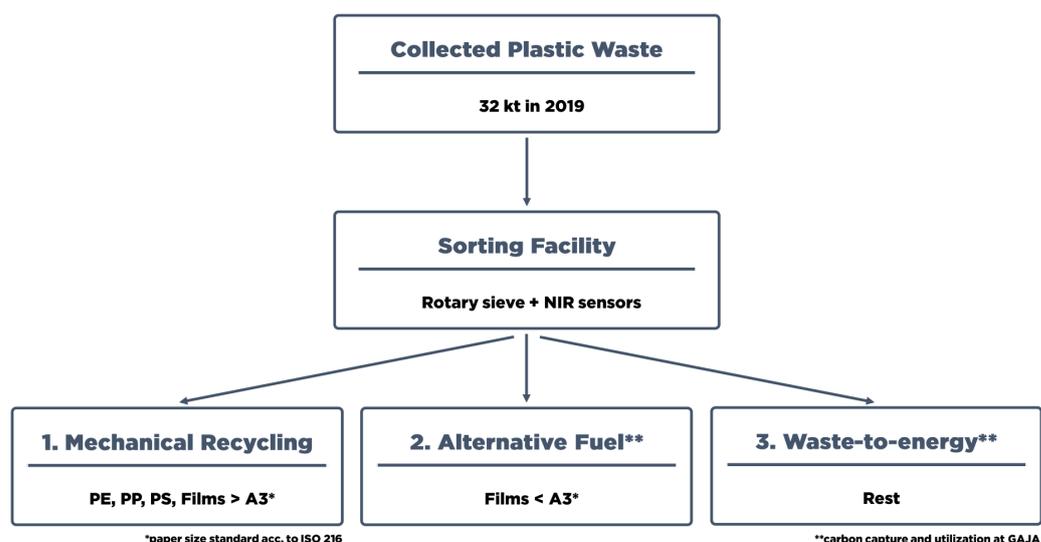
**Figure 2.** Summary of recommendations obtained from expert interviews to enhance plastics recycling in Iceland by improvements throughout the value chain.

Iceland mainly contributes to a CE with its collection schemes, however, a collection rate of only 28% indicates significant untapped potential in waste collection. In this regard, the harmonization of the various different collection systems should be pursued in order to increase the amount and homogeneity of recovered waste. Other than that, a recycling bin which is currently only obligatory should become mandatory, reducing the amount of valuable recyclates being lost in the residual waste which is not subject to any form of treatment. Moreover, no conclusive evidence was found that Skyr cups are suitable for an implementation to the DRS, as the disadvantages outweigh the theoretically higher collection and recycling rates (see Table 2). However, other products may be identified that fulfill the requirements for the deposit system benefiting overall waste collection.

The example of *Pure North Recycling* shows that domestic recycling may be suitable for homogeneous waste streams by using sustainable resources, such as geothermal energy and steam. However, sorting and treatment of mixed plastic waste is supposedly economically more efficient by collaborating with experts throughout Europe due to the small amount of domestic waste compared to other countries. Therefore, the interviewed experts expect that the current practice of exporting the majority of the domestic waste will prevail. In that regard, it is essential that the exported waste is of highest quality, which can be ensured by improvements upstream in the value chain.

Based both on the status quo, which was acquired by the semi-structured interviews, and the crucial scientific background, the authors suggest to invest in a comprehensive waste treatment and recycling scheme in Iceland, which is depicted in Figure 3 [43,44]. The general principle can be described as follows: the annual amount of collected plastic

waste (e.g., 32 kt in 2019) in Iceland is recommended to be sorted using two state-of-the-art techniques. First, the entirety of the waste should be sorted using a sieve drum to separate 2D products (e.g., films) and 3D products (e.g., Skyr cups, bottles, containers). Large 2D products remain in the drum whereas small 2D products and 3D products are sorted out. The large films (>A3 according to ISO 216 [45]) can be directly transferred to further treatment (path 1). Second, the segregated fraction should be further sorted using NIR sensors. This step is considered to separate polyethylene (PE), polypropylene (PP), polystyrene (PS), and small films. Although PE, PP, and PS are fractions of interest (path 1), the small films can only be used for alternative fuel (path 2). All waste, apart from these sorted fractions, is to be sent for thermal recycling (i.e., waste-to-energy; path 3).



**Figure 3.** Proposed comprehensive waste treatment and recycling scheme.

The proposed scheme is a viable alternative to the existing system, which is characterized by treating and recycling plastic waste abroad and which involves elevated greenhouse gas emissions due to long ways of transportation to specialized recyclers throughout Europe. Exploring a pathway to a predominantly national solution that is not yet established in any form would be another step towards the reduction in greenhouse gas emissions. Key factors for the successful transition are short ways of transportation and the re-use in the own country in accordance with the appropriate technology.

For the configuration of the required waste treatment and recycling facilities, a special focus should be on the design of a flexible recycling line that is tailored to relatively small amounts of waste and which can be adapted according to the specific needs for various different input materials. We propose to implement a recycling facility which is operated by a single company (or by a highly harmonized alliance of companies) to keep upfront investment costs at a minimum and to guarantee that the already limited amount of collected plastic waste is not further split up. Nevertheless, the amount of plastic waste is expected to increase in the future, which enables higher capacities in the facilities. If a complete recycling line is operated at a single site, bailing of the waste is not necessary. After sorting at a product level, the mechanical plastics recycling in path 1 recommends a grinding and washing step as preparation for re-granulating. For mechanical recycling, several machine producers are available which offer whole-system solutions usable for rigid and flexible input streams. Instead of paying for the export of waste, value is created by the production of various grades of recyclates, which can be either processed by Icelandic companies or exported. Although food-grade packaging products will be off-limits due to laws regulating food contact materials, products for the electrical and construction industries (e.g., buckets, tube clamps, which are produced by the Icelandic company *Bergplast* [40]) could be manufactured from recyclates directly

in Iceland. A further possible solution which can be used for small batch recycling is a two-stage process (e.g., duo-circ by ENGEL [46]), where flakes can directly be converted to injection molded products. Existing infrastructure at *Pure North Recycling* should be taken into consideration.

Path 2 and 3 are both ways to recover energy from a plastic feedstock that has reached the waste level. Against the current practice of costly exporting or landfilling materials not suitable for mechanical recycling (e.g., multi-material packaging, speciality polymers, composites), plastic waste should be used as an energy source due to its high calorific value. Path 2 suggests the use of small films as alternative fuel in, for example, cement kilns, where plastics substitute conventional fossil fuels. Hereby, up to one ton of CO<sub>2</sub> per ton of coal replacement can be saved by using plastics residue [47]. However, chlorine-based polyvinyl chloride (PVC) promotes corrosion in the plant, which is why a pre-sorted waste stream (i.e., films < A3) with a defined range in calorific value should be used [48]. Finally, the remaining part of the collected plastic waste is neither suitable for mechanical recycling nor alternative fuel to be sent to a waste-to-energy plant. Again, the high calorific value of the plastic enriched waste fraction is beneficial for the effective transition to energy. Nevertheless, conventional incinerators produce a significant amount of direct CO<sub>2</sub> emissions and the technology is considered as a carbon intensive way of power generation [49]. Recent developments in the field of carbon capture technology directly in Iceland can be observed in the construction of a biogas and composting plant, *GAJA*, where methane is produced [50]. Moreover, the direct air capture and storage plant *Orca*, in operation since 2021, which is able to remove CO<sub>2</sub> on a large scale [51]. Ideally, acquired know-how on carbon capture technologies should be meaningfully scaled in an industrial incineration plant designed for a less carbon intensive power generation. In addition to the remaining fraction of the collected waste, residual household waste should also be directed to the incineration plant, making landfilling obsolete. To sum up, the advantages and disadvantages of the proposed scheme are listed in Table 3.

**Table 3.** Advantages and disadvantages of the proposed comprehensive waste treatment and recycling scheme.

| Advantages                                | Disadvantages                      |
|---|------------------------------------|
| CO <sub>2</sub> emission optimization     | High investment costs              |
| Cheaper/short line                        | Frequent retooling of the machines |
| Tailored for small amounts                | Know-how must be acquired          |
| Higher value creation                     |                                    |
| Short transport                           |                                    |
| Re-use in own country                     |                                    |
| Independent of incineration plants abroad |                                    |

Furthermore, it has to be noted that circular economy concepts for plastics feature also alternative routes apart from the three paths included in the proposed waste treatment and recycling scheme [43,44]. However, chemical recycling or solvent-based recycling are considered not viable for Iceland due to significant disadvantages compared to the other options, which are mainly elevated investment costs and high energy requirements [24,52]. Moreover, PET bottles which are homogeneously collected in the deposit system are not subject to the Icelandic recycling system, as the quantity of available material does not justify the investment costs required to achieve a recycle quality comparable to well-established European PET recyclers.

We emphasize that our proposed comprehensive waste treatment and recycling scheme for Iceland is based on our scientific knowledge, and that it supports the EU’s efforts to reach both packaging waste recycling targets and net-zero climate change emissions by 2050 [21,53]. However, the economical and legal framework must be evaluated by those responsible within the Icelandic government and companies also by taking environmental incentives into consideration.

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## Appendix A. Interview Guide

1. What is the public perception of plastics in Iceland?
2. What would you change in the current recycling value chain?
3. Which laws and regulations should be changed in regard to recycling and how should they be changed?
4. Which goal should be pursued in plastics recycling and how does your company or institution contribute to that?
5. What are the challenges and requirements of adding a packaging product to the deposit system?
6. What would change in your company or institution if the deposit system was extended?
7. How do you think the population would receive such a change?

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