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A System Dynamics Supply Chain Analysis for the Sustainability Transition of European Rolled Aluminum Products

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Abstract: This research presents a system dynamics model to study the interaction among demand and supply evolutions, government regulations, sustainable adoption trends, investments in different decarbonization technologies, and environmental requirements for the European Aluminum Rolled Product Supply Chain (ARPSC). It allows stakeholders to assess the quantitative impact of investing in decarbonization technologies on supply chain sustainability. Investing in decarbonization technologies reduces greenhouse gas (GHG) emissions. The most substantial GHG emission reductions can be achieved if upstream ARPSC actors invest according to an aggressive investment strategy between 2031 and 2040. However, even with an aggressive investment strategy, investing in decarbonization technologies alone is likely to be insufficient to achieve the European Green Deal goals. Furthermore, barriers to investment in decarbonization technologies and a low rate of progress in doubling the European Union's circularity rate may put extra stress on achieving the European Green Deal goals for the European ARPSC. Instead, ARPSC actors will additionally need to optimize the recycling of aluminum rolled products and adopt strategies for resource sufficiency, e.g., by sharing cars and using packaging multiple times.

Keywords: demand and supply dynamics; sustainable supply chains; environmental impact; economic impact; system dynamics; aluminum supply chain

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1. Introduction

The global effort to limit the temperature increase to 1.5 °C above pre-industrial levels to curb climate change, as stated in the Paris Agreement [1], presents many extra challenges for supply chain (SC) partners. The environmental reforms imposed on economic activities by the European Union (EU) governing bodies in the European Green Deal [2] further complicate pre-existing SC challenges, such as supply and demand dynamics, increasing customer requirements, and implementing novel operations and technologies. The transition to sustainable supply chains (SSCs) is particularly challenging for energy-intensive industries [3].

Sustainable supply chain management considers the economic, environmental, and social pillars of sustainable development in managing material, information, and capital flows [4]. Energy-intensive industries can become more sustainable by, for example, using different energy sources and heat [3]. In particular, the European aluminum industry focuses on shifting towards renewable energy, decarbonizing the process by implementing reduction technology (e.g., introducing inert anodes), and adopting technological changes to increase the share of reused and recycled aluminum [5]. Moreover, the European aluminum industry must also optimize recycling levels [6]. Recycling aluminum offers significant environmental benefits, as its environmental impact in terms of GHG emissions is 20 times lower than that of primary aluminum [7]. Unfortunately, the amount of secondary aluminum will not be sufficient to meet the forecasted growth in demand for aluminum rolled products (ARPs), either in the EU [6] or globally [8]. As a result, a large amount of primary, energy-intensive aluminum will still need to be produced. To enable the transition to a low-carbon Aluminum Rolled Product Supply Chain (ARPSC), all SC partners involved must have a thorough understanding of how the evolution of demand and supply will impact the GHG emissions of the ARPSC in the long run and which investments in new technologies are required to help them achieve this goal. As the European ARPSC is an energy-intensive industry that requires its production to keep up with the projected growth in demand, it simultaneously needs to accelerate its ambition to become more sustainable. Hence, the European ARPSC is considered an appropriate case study for this research.

The objective of this research is to examine the impact of potential investment strategies on the sustainability of the ARPSC and its partners. This paper uses the European ARPSC as a case study to develop an SD model that incorporates a combination of applicable EU government regulations, technological advances to produce low-carbon aluminum, and environmental requirements on top of the economic pillar and to formulate managerial and policy recommendations to support long-term strategies as by Lu et al. [9]. The research commissioned by the European Aluminium Association and conducted by Le Den et al. [5] on the decarbonization of the European ARPSC is used as the basis to validate the findings of the SD model.

Pinto and Diemer [10] already captured the European steel supply chain dynamics in a system dynamics (SD) model. They simulated multiple supply chain integration scenarios to close the loop and improve raw material self-sufficiency. Although the steel industry is an important, energy-intensive industry, the model developed by Pinto and Diemer [10] cannot be directly applied to other energy-intensive industries because the manufacturing process is different. Moreover, new policy developments in energy-intensive industries that enable the transition to an SSC, such as the European Green Deal and the Carbon Border Adjustment Mechanism (CBAM), are not incorporated.

Pinto and Diemer [10] noted that the pricing and costing of steel and the heat and electricity used in the production process are not incorporated in the model. However, heat and electricity consumption, operating costs and profit, and government regulations are relevant elements for the SSC, as identified by Rebs et al. [11], who discussed potential causalities among the Ecological System (i.e., biodiversity, materials), Social System (i.e., government, community), and Economic System (i.e., finances, quantities, pollution) for the SSC. Similar to Pinto and Diemer [10], other models (e.g., [12–16]) capture important elements for shifting toward an SSC in dynamic models but do not incorporate government regulations, technological advances, and environmental and economic parameters or their impact on long-term supply and demand evolutions.

The objective of this research is to evaluate the impact of various decarbonization technology strategies in enhancing the sustainability of the European ARPSC to limit the temperature increase to 1.5 °C above pre-industrial levels to curb climate change. The contribution of this paper is threefold. First, it proposes an SD model that integrates the evolution of the demand and supply of primary and secondary resources, paying particular attention to the fraction of low-carbon primary resources, investments for different decarbonization technologies, environmental impacts, applicable EU government regulations, and sustainable adoption trends. Second, it examines the impact of different decarbonization investment strategies on multiple supply chain actors over the following decades. Third, this research develops and quantifies scenarios that can support the European aluminum industry in making strategic decisions to limit global warming and identify the impacts on individual supply chain partners.

The remainder of this paper is structured as follows. A focused literature review is presented in Section 2. Section 3 presents the methodology for developing an SD model for the European ARPSC. The proposed model is validated in Section 4. Potential future scenarios are analyzed and discussed in Section 5. The last section concludes the paper, identifies the academic and industrial implications of the research, and presents directions for future research.

2. Literature Review

This section first covers the literature on system dynamics. Second, the literature on sustainable supply chains is discussed. Finally, the research gap and objectives are stated.

2.1. System Dynamics

A growing body of literature is being published on sustainable supply chain management using different methodologies [17]. However, there is only limited quantitative research on sustainable supply chains using methods, such as Life-Cycle Assessment (LCA) and Multi-Criteria Decision-Making (MCDM). LCA examines the overall environmental impact of a product but does not include cost and risk assessment [18]. MCDM allows for the integration of the different components of a sustainable supply chain. It is also used to examine challenges, performance, and barriers to sustainable supply chain management [19]. MCDM typically tends to optimize economic or environmental criteria or balance trade-offs between conflicting objectives in sustainable supply chain management research [18].

Since the objective of the current study is to examine the impact of potential investment strategies on supply chain sustainability in a dynamic environment, rather than finding an optimal solution or examining the environmental impact without considering costs and risks, LCA and MCDM are deemed inappropriate for this research. Moreover, considering sustainable development policy-making modeling approaches, multi-agent modeling and system dynamics are both considered to be suitable decision support models [20,21]. The design and monitoring of sustainability policies put emphasis on models to be able to capture the complex dynamics of interconnected variables and sustainability-related subsystems [22]. Systems thinking and system dynamics (SD) are well fit for the analysis of complex systems and their underlying dynamics and are therefore powerful modeling tools to support decision support and policy making [20,22–24]. To advance our understanding of the complex behaviors and interactions of different actors and entities in an SSC, a systems thinking approach is adopted [11]. Systems thinking provides a holistic view of a complex system in which the constituent parts are interconnected, and actions are not isolated [23]. Systems complexity is rooted in three main types of dynamic interactions between systems entities [21]: delays, i.e., temporal differences between actions and their consequences; non-linear relations in which one action can cause more than one consequence and one consequence can be caused by more than one action; and feedback loops, in which the output of an entity also becomes its input. System dynamics (SD) is a suitable methodology to model the dynamic interactions between system entities [25]. Moreover, SD is a good methodology to explain and predict the behavior of real-life SCs, develop and test future policies and strategies [26,27], and capture the dynamic effects of different entities within a system [23,27]. It should also be noted that many sustainability-related complex systems face the lack of accurate measurements and immaturity of theories and are susceptible to unpredictable external perturbations and non-linear system behavior [28]. System dynamics is suitable to deal with all these constraints [22].

One of the first globally disseminated results of dynamic systems modeling predicting the complex interaction among the economy, ecology, and society is the World3 system dynamics model [29] that was used to assess multidimensional cause–effect relations at the global level and their projection up to the year 2100. Two follow-up reports, which however received less attention, were published in recent decades by Meadows et al [30] and Randers [31]. Randers, one of the co-authors of Limits to Growth [29], designed a new updated systems dynamics model, Earth4All, facilitating the identification of decoupling GDP from ecological impact scenarios, which has been used in the follow-up report of the Club of Rome, entitled “Earth for All: A Survival Guide for Humanity” [32].

2.2. Sustainable Supply Chains

Several sustainable policy-supporting initiatives in place drive the journey towards sustainable supply chains, such as The Paris Agreement [1], The Sustainable Development Goals (SDGs) [33], The European Green Deal [2], and the Inflation Reduction Act [34], in the USA. All these policies aim to have an absolute decoupling between GDP growth and the adverse environmental and social effects of this growth. Currently, only a relative decoupling has been realized, and planetary boundaries as defined by Rockström et al. [35] become increasingly under stress. This has given rise to other schools of thought, such as degrowth, post-growth, steady-state economics, and the donut economy, which question the need for economic growth in the global North.

In the European Union, the "Net-Zero Industry Act" [36] sets a target for Europe to produce 40% of its annual deployment needs in net-zero technologies by 2030, based on National Energy and Climate Plans (NECPs) and to capture 25% of the global market value for these technologies. However, the final goal of the decarbonization journey in the EU is to reach net zero emissions by 2050 [2]. The IEA [37] remarks that despite growing investment in clean energy innovation, greater policy support is needed to get on track for net zero, and they advocate for the necessity for more international initiatives to decarbonize sectors, like heavy industry and long-range transport. The realization of less carbon-intensive and finally carbon-neutral supply chains has to be supported by the emergence of new technologies. The NECPs intend to increase the use of less carbon-intensive technologies [36].

To be able to support these policies in implementing new technologies to decarbonize the supply chain and make the supply chain more sustainable, research needs to consider the entire sustainable supply chain. Research on the evolution of demand and supply in SSCs is limited, particularly concerning the combination of environmental and economic variables, technological developments, and government regulations with demand and supply in SSCs. Sverdrup et al. [16] assess the long-term global evolution of aluminum reserve volumes and demonstrate that substituting a significant portion of copper, iron, steel, and stainless steel with aluminum could result in aluminum scarcity. Suryani et al. [38] developed an SD model for the Indonesian beef SC at the national level, taking into account uncertainties in supply caused by climate change, demand, and distribution. Aivazidou et al. [39] present an extensive SD model to capture the dynamic relationships among water usage, green market behavior, and corporate profitability for a wine SC. They consider the impact of technological interventions in agriculture on environmental and economic sustainability. Guo et al. [15] evaluate how different combinations of aluminum production technologies would impact the energy conservation ambitions of the Chinese aluminum SC. They use four energy pricing scenarios to evaluate 16 technological combinations and propose a decision-making method based on the Data Envelopment Analysis for evaluating and selecting energy-saving technology routes for the Chinese aluminum industry. Pinto and Diemer [10] examine the evolution of iron demand and supply for the European steel industry under the environmental regulation of greenhouse gas (GHG) emissions reduction and varying levels of economic sustainability for the entire industry. Using SD modeling and life cycle assessment, Pinto and Diemer [10] investigate how the circularity of the European steel industry could be achieved through potential SC integration strategies. Zimon et al. [12] align sustainable supply chain management practices with the United Nations (UN) sustainable development goals. Sharifi et al. [13] maximize profit and minimize CO_2 emissions for the soybean supply chain. Zahraee et al. [14] examine the impact of changes in transportation and production technologies for the palm oil biomass supply chain on environmental sustainability.

2.3. Research Gap

The structure of a supply chain [40] and collaboration in the supply chain [41] influence the sustainability and profitability of a supply chain. Moreover, the environmental impact of a supply chain can reduce the profitability of the supply chain [42]. Therefore, to achieve the objectives of the EU Green Deal [2], SC actors need to consider additional environmental constraints on economic activities. Despite the large number of studies on the impact of either economic or environmental activities on supply chain evolutions, to our knowledge, no study has investigated their interactions simultaneously in a single model.

Several studies examine the elements of demand, supply, and sustainability for energy-intensive industries; however, no study examines the interactions among decarbonization technologies, government policies, and environmental goals for sustainable supply chains in energy-intensive industries. Therefore, the objective of this research is to examine the impact of potential investment strategies on the sustainability of the ARPSC and its partners. It contributes to the existing literature by proposing a novel SD model that integrates demand and supply evolutions of SSCs in combination with investments for decarbonization technologies, environmental impacts, and sustainable adoption trends. Furthermore, this study examines the impact of different investment strategies on multiple actors in the supply chain to enable stakeholders to make strategic decisions to limit global warming.

3. Methods

To address the shortcomings of existing models for supporting sustainability improvements in supply chains, an encompassing system dynamics (SD) model is developed and applied to the European ARPs industry. SD models use stocks and flows to describe real-world systems. Stocks include inventories, e.g., primary aluminum, and flows indicate rates of increase or decrease in stocks, e.g., annual primary aluminum production. Stocks and flows are connected through causal links, represented by arrows.

The proposed SD model for the European Aluminum Rolled Products Supply Chain (ARPSC) covers the EU-27, the UK, and the EFTA, as does the research of Le Den et al. [5] for European Aluminium (EA), an association for the metals value chain for the aluminum industry in 30 European countries [43]. European aluminum products are divided into unwrought and wrought products (Aluminium-guide.com, accessed on 11 October 2024). The research scope is limited to semi-finished rolled wrought products (aluminum sheet and foil) further referred to as Aluminium Rolled Products (ARPs). This means that the SD model covers approximately 65% of the market share of aluminum in Europe. Automotive, Packaging, and Building and Construction are the three main market segments of European ARPs, covering more than 80% of its annual volume [44].

To model the dynamics in these markets, data and insights from the literature, from industry associations, such as European Aluminum (EA) and the International Aluminium Institute (IAI), and data gathered during consultations with industry experts active at various stages of the ARPSC are used. Data and insights from the literature, industry experts, and industry associations, such as EA and IAI, are included in the following subsections and in the model documentation. The initial values for the stocks of the system dynamics model are mostly based on data of 1990. The exogenous parameters are based on different datasets as explained below. The endogenous variable values are simulated and are compared to available data to validate past and future behavior. The documentation of the model is included in the Supplementary Materials. Figure 1 provides an overview of the system boundaries of this research and the interactions between different domains: economic, environmental, and supply and demand. These domains are addressed in the following subsections. The EU Green Deal forces changes to the European ARPSC to become more sustainable.

Because the European ARPSC is complex, the ARPSC SD model is decomposed into three interacting components. These components are discussed in the following sections. Figure 2 provides a causal loop diagram to display the variables, concepts, and interacting components of the proposed system dynamics model. The indicated interactions are addressed in more detail in the following subsections and written in *italics*. The first component, highlighted in green in Figure 2, relates to demand evolution (Section 3.1.1) and supply evolution (Section 3.1.2). The second component, highlighted in black in Figure 2, relates to the environmental aspects of the ARPSC (Section 3.2). The third component, highlighted in red in Figure 2, represents the economic pillar of the ARPSC (Section 3.3). Table 1 provides details on the most important feedback loops visualized in Figure 2.

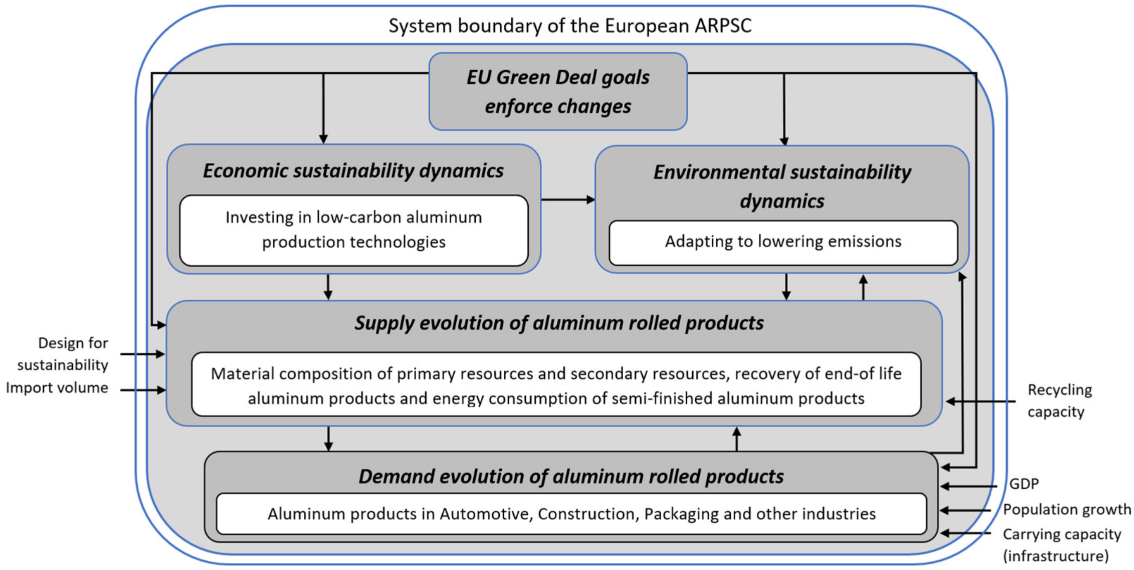

Figure 1. System boundary of the European ARPSC SD model. The arrows indicate the influence of one domain on another. The variables outside the blue lines are considered exogenous to the system.

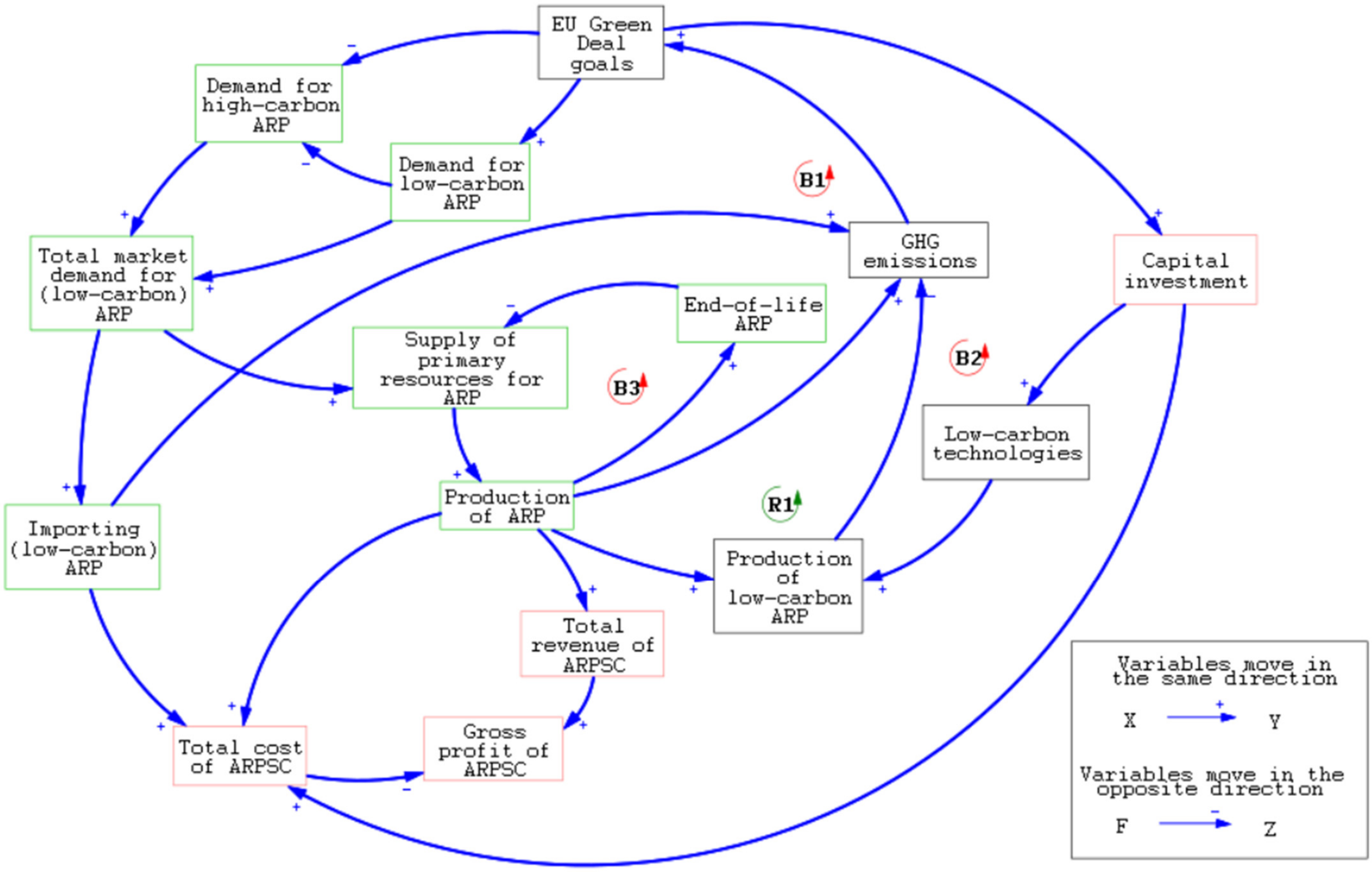

Figure 2. Causal loop diagram (CLD) of the proposed SD model.

Table 1. Most important feedback loops of the causal loop diagram.

Loop	Variables
B1: Import of (low-carbon) aluminum	EU Green Deal goals—Demand for high-carbon ARP—Total market demand for (low-carbon) ARP—Importing (low-carbon) ARP—GHG emissions—EU Green Deal goals
B2: Investing in low-carbon technology	EU Green Deal goals—Capital investment—Low-carbon technologies—Production of low-carbon ARP—GHG emissions—EU Green Deal goals
B3: Supply chain of ARP	Supply of primary resources for ARP—Production of ARP—End-of-life ARP—Supply of primary resources for ARP
R1: Production of low-carbon ARP	EU Green Deal goals—Demand for high-carbon ARP—Total market demand for (low-carbon) ARP—Supply of primary resources for ARP—Production of ARP—Production of low-carbon ARP—GHG emissions—EU Green Deal goals

3.1. Demand and Supply Evolution of Aluminum Rolled Products

3.1.1. Demand Evolution of Aluminum Rolled Products

While gross domestic product (GDP) growth, population growth, and legislation are the three main drivers of the *Total market demand for* (*low-carbon*) *European ARPs* [8,15,45], each customer market segment (Automotive (ADA_t), Packaging (ADP_t), and Building and Construction (ADC_t)) also has its specific demand forecast. The demand consists of high-carbon ARP and low-carbon ARP depending on customer demand driven by the EU Green Deal goals. The inflow-driven approach [45] based on regression models is used to predict future demand. Compared to the stock-driven approach, this is a less data-intensive method [46] and is used by the majority of the reviewed studies estimating future metal demand [45]. Altogether, the *total demand for Rolled AL* (ADT_t), consisting of low and high-carbon ARP, in a period t is based on the combination of the above customer market segments and other market segments (ADO_t):

$$ADT_t = ADA_t + ADP_t + ADC_t + ADO_t \text{ [Kilotons/year]} \quad (1)$$

Each customer market segment is driven by the GDP and population growth. Similarly to Inghels et al. [21], the population is a combination of the number of births, deaths, emigration, and immigration within Europe. The population size in Europe was set to 2.393×10^8 people at the start of the simulation in 1990 [47] and subsequently readjusted in each time step to match the expected growth of 1.346×10^6 people per year until 2026. After 2026, the population in Europe is expected to decline by 1.570×10^6 people each year [47]. It is assumed, based on Inghels et al. ([21], that the annual population increase grows linearly over time from 1990 to 2026 and experiences a linear decrease between 2026 and 2050.

The GDP is expected to grow linearly by 0.0154% per year based on data from 2010 to 2020 [48]. Together with the carrying capacity, which represents the saturation of the customer market segment, the net increase in the customer market segment is predicted [21]. Moreover, the combination of the net increase prediction for the market segment in combination with the population development over time, the actual growth rate for the customer market segment is determined. That growth rate, in combination with discarded products, determines the demand for new products for a specific market segment.

The Automotive market segment is the largest ARP market segment, accounting for 38% of total European demand [44]. It is assumed that 1.64×10^8 cars were on the European market in 1990 [49]. Its primary focus is on passenger cars, which account for 87% of the total stock of registered automotive vehicles in Europe [50]. The major demand drivers for the sales volume of passenger cars are GDP, population growth, and the number of discarded cars [21]. The proposed SD model uses the approach developed by Inghels et al. [21] to estimate the number of future cars. Significant future growth in the European ARP demand in the Automotive market is expected to stem from the transition to more environmentally friendly vehicles in the form of Battery Electric Vehicles (BEVs), which require more aluminum [51]. On average, the weight of aluminum in a car is 0.095 tons in 1990. The weight of a car is expected to increase by 0.0029% annually from 1990, and it is expected to increase even further by 0.0033% per year from 2020 [51]. An important factor that could inhibit this growth is the expected shift in consumer preference towards using shared cars rather than owning them [52,53], which will reduce the demand for passenger cars based on expected growth. The demand for shared cars is expected to increase in the future. The annual demand for aluminum rolled products in the Automotive market segment (ADA_t) is a product of the number of new cars (NA_t), the average weight of a new car ($\hat{W}A_t$), and the average fraction of aluminum in a new car ($A\hat{W}A_t$):

$$ADA_t = NA_t \times \hat{W}A_t \times A\hat{W}A_t \text{ [Kilotons/year]} \quad (2)$$

The Building and Construction market segment accounts for 11% of the total demand for European ARPs [44]. The demand for European ARPs in this market segment is mainly influenced by GDP and population growth, which triggers the construction of new buildings [8]. It is expected that 75% of all buildings are residential buildings [54]. According to consulted experts, a residential building uses 5% aluminum per square meter on average. The renovation of existing buildings and the need to comply with EU regulations on the energy efficiency of buildings also contribute to changes in European ARP demand for buildings [55]. The rate of renovation for non-residential buildings started at 1% of the buildings in 1990 and increased by 0.04% each year [54]. The demand for aluminum rolled products in the construction market segment (ADC_t) is determined by factors, such as the average weight of aluminum per square meter of floor space (AWR_t) (for residential buildings) and $A\hat{W}N_t$ (for non-residential buildings), the amount of renovated floor space (RR_t) (for residential buildings) and (RN_t) (for non-residential buildings), and the amount of new building floor space (NC_t):

$$ADC_t = (AWR_t \times ((0.75 * NC_t) + RR_t)) + (A\hat{W}N_t \times ((0.25 \times NC_t) + RN_t)) \text{ [Kilotons/year]} \quad (3)$$

The Packaging market segment accounts for 22% of the total demand for European ARPs [44]. In addition to GDP and population, consumer awareness and concerns about sustainability are additional demand drivers for sustainable packaging in the consumer goods market, including aluminum cans [56–58]. Based on studies of consumer preference for sustainable packaging, the Packaging market is expected to grow slightly [59,60]. The demand for aluminum rolled products in the packaging market segment (ADP_t) is a product of the average weight of aluminum in a square meter of a new packaging (AWP_t), the consumer usage rate of aluminum packaging (B_t), and new aluminum packaging (NP_t):

$$ADP_t = AWP_t \times NP_t \times B_t \text{ [Kilotons/year]} \quad (4)$$

An ordinary least squares (OLS) regression estimates the demand for European ARPs in other market segments (ADO_t) using the data from 1990–2019 obtained from IAI [61]. Figure 3 presents the demand evolution of the four different customer market segments that form together the overall demand for rolled aluminum in Europe. The curve between 1990 and 2020 of the demand for the four categories is based on available data on the actual demand pattern. The curve between 2020 and 2050 is based on the inflow-driven approach based on regression models to predict future demand.

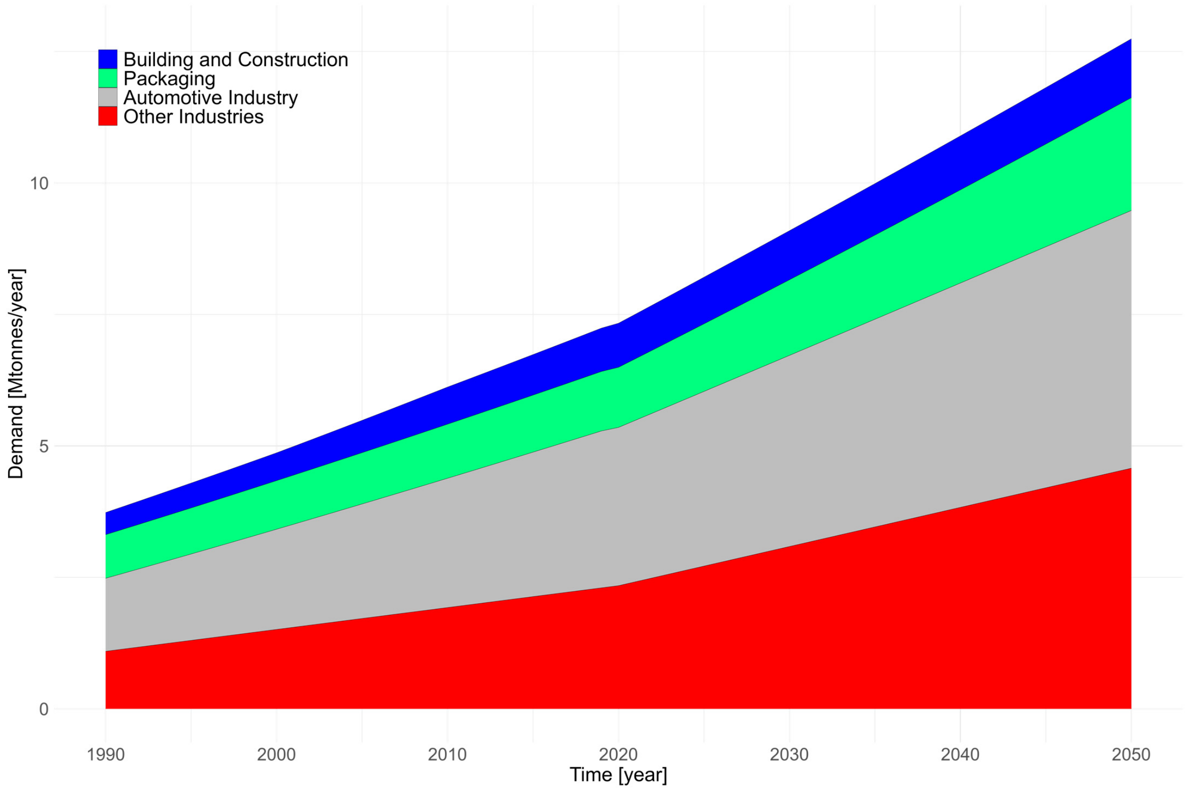

Figure 3. Evolution of European aluminum demand for Building and Construction, Packaging, Automotive Industry and Other Industries forming the total demand for rolled aluminum in Europe.

3.1.2. Supply Evolution of Aluminum Rolled Products

The European ARP processes that form the life cycle of the SD model are based on data from IAI [61] (annual data from 1990–2019), EA [62] (constants), and Bertram et al. [63] (constants). Bertram et al. [63] is used for the determination of the stocks and flows of the European ARPSC and the corresponding uncertainty calculations of 2014. The constants from EA [62] are used for the transformation of the intermediate products in the different supply chain stages. Moreover, the annual data on primary aluminum production in Europe from 1990 to 2019 [61] are used for the calibration of the supply chain of the European ARPSC. The life cycle includes different supply chain stages, such as product design, raw material extraction and processing, product manufacturing and delivery, product use, and end-of-life disposal/new life, as proposed by Inghels [64]. In the life cycle of the European ARPSC, bauxite extraction, alumina production, and primary aluminum production are considered key stages of the upstream SC. In contrast, rolled aluminum production and post-consumer scrap refining are assumed to be part of the downstream SC [65]. This together forms the *Production of ARP*. To model, calibrate, and validate the circular behavior of the European ARPSC, life cycle data between 1990 and 2019 from IAI [61] and EA [11] are used. It is assumed that the average life cycle data between 1990 and 2020 are maintained for the future. Demand that cannot be met by European supply is met by the *import of (low-carbon) aluminum rolled product* (I_t), which is assumed to be around 50% on average (IR) [44]. The demand for European aluminum production (ADM_t) in a period t is defined by the following:

$$ADM_t = ADT_t - I_t \text{ [Kilotons/year]} \quad (5)$$

whereas the import equals the following:

$$I_t = ADT_t \times IR \text{ [Kilotons/year]} \quad (6)$$

The final life cycle phase is the recycling of *end-of-life ARP*, which generates post-consumer scrap, as presented in loop B3 in the CLD. In the presented SD model, discarded rolled aluminum-containing products are sent to a post-consumer scrap inventory that is replenished according to a post-consumer scrap rate for each customer segment. Around 50% of scrap is not used within Europe [61]. To estimate the post-consumer scrap, the average scrap rate is calculated based on 1990 to 2019 data [61]. The scrap rate (SR_t) is based on a first-order material delay of the average lifespan of aluminum (L), following the approach of Inghels et al. [21], and the recyclability fraction (RF) in each customer segment. The recyclability fraction for each customer segment is based on the input of experts working in the aluminum industry. According to European Aluminium [62], the average lifespan of aluminum in the Automotive, Building and Construction, and Packaging market segments is approximately 12 years, 60 years, and 1 year, respectively. The production that cannot be fulfilled by post-consumer scrap is fulfilled by the *supply of primary resources for ARP* to meet the *Total market demand for* (*low-carbon*) *ARP.*

$$SR_t = \frac{ARP_t}{L} \times RF \text{ [Kilotons/year]} \quad (7)$$

Post-consumer scrap from ARPs can be used in non-ARPs (e.g., extrusion) and vice versa. Due to a lack of available data on this loop leakage, it is assumed that all post-consumer scrap from ARPs will be used to produce new ARPs.

3.2. Environmental Pillar

To achieve the UN Paris Agreement, the *EU Green Deal* [2] forces EU industries to reduce their net GHG emissions to zero by 2050 [66]. It requires that cumulative emissions from European aluminum production from 2020 to 2050 remain within the EU's established carbon budget for aluminum production in Europe of 339 MtCO_2e [5]. In 2005, the EU introduced the Emissions Trading System (ETS). Companies subject to the ETS should ensure sufficient carbon allowances for their emissions. Due to the technological limitations in reducing *GHG emissions* and to ensure competitiveness with non-EU competitors [67], the European ARPSC receives almost 100% free carbon allowances for its production through the ETS [68]. The free carbon allowances greatly relax the enforcement of EU Directive 2020/0036 [69] for the ARPSC. The introduction of the Carbon Border Adjustment Mechanism (CBAM) in 2023 means that the allocation of free allowances will be phased out from 2026 onwards. The CBAM aims to promote cleaner production by ensuring that the carbon price of imported goods is similar to that of domestic goods [70]. Moreover, B2B customer pressure and global competition are increasingly forcing companies in the European ARPSC to strategically plan to increase their low-carbon aluminum production in the long run [8]. Low-carbon aluminum is defined as aluminum produced with less than 4.0 metric tons of CO_2e emissions for every ton of metal produced [71,72]. The dynamics of the production of low-carbon aluminum are reflected in feedback loop R1 in Figure 2. The exact dynamics of ETS in relation to CBAM are beyond the scope of this model and research. CBAM and ETS are used only as input to the dynamics surrounding the environmental domain.

The *EU Green Deal goals* require the aluminum industry to become more sustainable leading the investment in decarbonization technologies through *Capital investment*. To analyze the decarbonization pathway of the European aluminum industry, the proposed SD model uses the investment (M_t) amounts for decarbonization technologies from the industry research report of Le Den et al. ([5]; p. 51, Table 12) compared to the total expected investment amounts (TM). The investment in decarbonization technologies or in other words *low-carbon technologies* is presented in the CLD by loop B2. This increases the *production of low-carbon ARP*. In addition, the SD model extends the analysis of Le Den et al. [5] by integrating three possible investment adoption trends at different time intervals. The three adoption trends are derived from a combination of research [73–75] which addresses different perspectives of technology diffusion for different technologies. The three possible adoption trends formulated in this research follow a progressive investment strategy, constant investment strategy, or aggressive investment strategy over time, as shown in Figure 4. In the following sections, the progressive investment strategy is referred to as a slow trend, the constant investment strategy remains a constant trend, and the aggressive investment strategy is referred to as a fast trend. For simplification reasons, it is assumed that the decarbonization technology becomes operational right away after investment. The adoption trends are also used to move from the current situation, in which mostly high-carbon aluminum is still produced and imported, to a situation in which 100% low-carbon aluminum is produced by 2050. The analysis of expected investments in decarbonization technologies reported by Le Den et al. [5] is extended by testing the impact of low-carbon aluminum imports on GHG emissions. The *import of low-carbon aluminum* required by customers is modeled as a fraction of the total demand for aluminum imports. The dynamics of importing low-carbon aluminum is visualized by loop B1 in Figure 2. The global warming potential (GWP) [62] reflects the environmental impact of increasing *low-carbon aluminum production*. The exogenous variables to determine the GWP in combination with annual production are based on constants [62]. The annual emissions associated with each intermediary product and post-consumer scrap in the European ARPSC ($GWPI_t$) are calculated to incorporate the overall GWP of the European ARPSC (GWP_t) or in other words the *GHG emissions*. High-carbon and low-carbon aluminum are differentiated within the calculations. The equations are formulated from the high-carbon perspective with the GWP of every intermediate product in tons CO_2 ($GWPIR$).

$$GWP_t = \sum GWPI_t \text{ [Tons CO}_2\text{/year]} \quad (8)$$

whereas the general formulation for GWP for all intermediate products ($GWPI_t$) is as follows:

$$GWPI_t = ARP_t \times GWPIR \times (1 - \frac{M_t}{TM}) \text{ [Tons CO}_2\text{/year]} \quad (9)$$

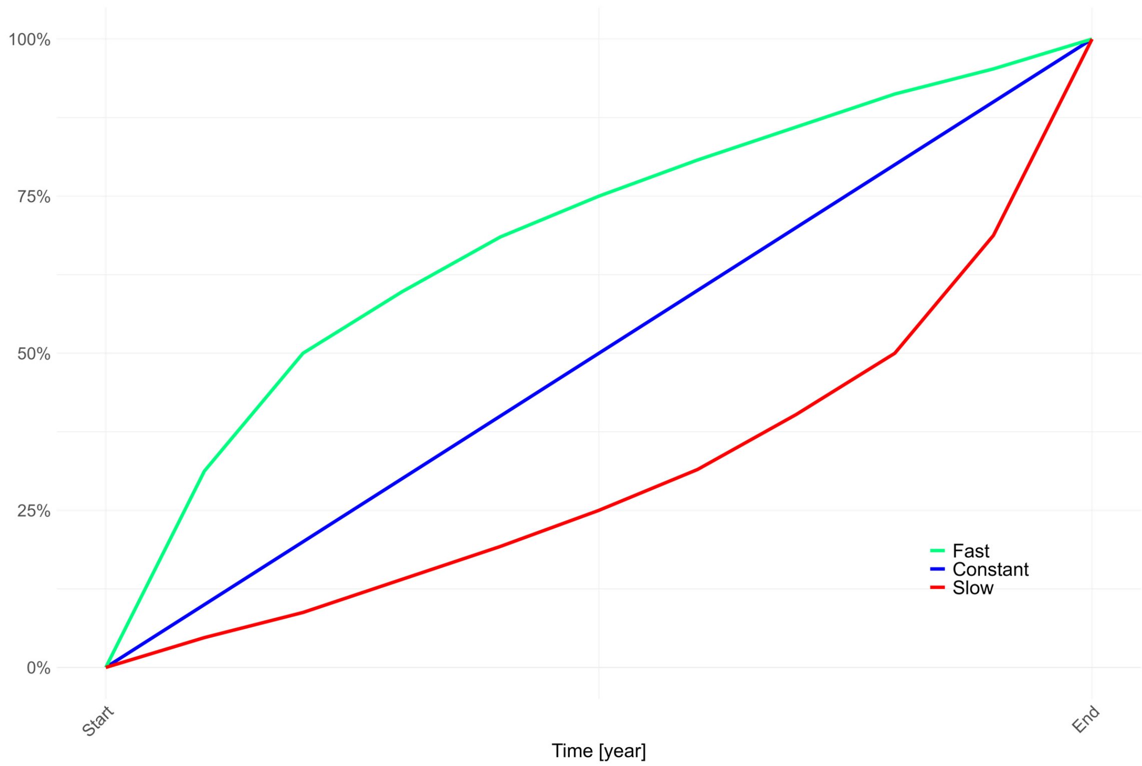

Figure 4. Adoption trends (initially fast, constant, or initially slow) in using the fraction of low-carbon aluminum production to meet customer requirements in the long run.

3.3. Economic Pillar

Raw materials, production processes, and energy sources generate GHG emissions in the ARPSC [62]. To decarbonize the European ARPSC, investments in emission reduction technologies, e.g., to replace current high-carbon energy sources, are required. The SD model input for the total investment per decade for each SC actor is based on the research of Le Den et al. ([5]; p. 51, Table 12]), presented in Table 2. The adoption trends shown in Figure 4 are applied to each decade for every SC actor. It is assumed that all SC actors fully cooperate and are willing to invest the required amount of money. This allows the effect of different investment strategies for different decades and SC actors to be illustrated and the impact on GHG emissions to be assessed. Investing in decarbonization technologies or in other words *capital investment* reduces the carbon intensity of production proportionally and consequently reduces GHG emissions.

Table 2. Expected investment costs per decade for each SC actor; note: reprinted from Science-based decarbonization pathways (p. 51) by [5], Ramboll. Copyright 2023 by Ramboll.

	Primary Aluminum Production					Semi-Fabrication		Recycling		Total
	Bauxite Mining	Alumina Refining	Smelter	Anode/Paste Production	Primary Cast House	Sheet Production	Extrusion	Remelting	Refining	
2021–2030 [MEUR]	(n.a.)	195	1535	25	15	30	15	110	55	1980
2031–2040 [MEUR]	(n.a.)	500	19,480	215	115	300	70	1035	500	22,215
2041–2050 [MEUR]	(n.a.)	110	8200	15	10	15	85	230	115	8780
2021–2050 [MEUR]	(n.a.)	805	29,215	255	140	345	170	1375	670	32,975

The capital required to increase the production of low-carbon aluminum affects the profitability of the ARPSC. The *gross profit of ARPSC* is measured by deducting *total costs of ARPSC* (i.e., total material costs, total energy costs, total labor costs [10], total transportation costs (Freightos Data, n.a.), total capital costs [10], conceptual tax of CBAM) from *total revenue of ARPSC* (i.e., annual revenue from high-carbon products and annual revenue from low-carbon products (data based on inputs from industry experts)).

3.4. Assessment Criteria

A key performance indicator (KPI) is defined to assess the impact of investment strategies on decarbonization technologies. The Global Warming Potential (GWP) expressed in the cumulative CO_2 equivalent is of interest to the European ARPSC. European aluminum production from 2020 to 2050 should remain within the so-called carbon budget for aluminum production in Europe of 339 $MtCO_2e$ [5]. This means that the GWP output is only measured from 2020 onwards and the CO_{2e} emitted in the following years are added to the previous total emissions. Each year, the cumulative GWP output is compared to the carbon budget for aluminum production in Europe to monitor the achievement of the European Green Deal goals.

4. Validation of the System Dynamics Model

The SD model is run over a 61-year time horizon, from 1990 to 2050. The first 31 years of the simulation (1990–2020) represent historical behavior, and the endogenous variables are used to calibrate the SD model. Mainly IAI [61] data are used for calibration. The IAI data are reported on a yearly basis and cover a timeframe from 1990 to 2020. The last 30 years of the simulation, which uses out-of-sample forecasting, (2021–2050) show the different situations for the different scenarios. A period of 61 years is sufficiently lengthy to address the targets set by the European Green Deal to reduce GHG emissions to net zero by 2050. Moreover, it permits the use of expected investment costs for decarbonization technologies from Le Den et al. [5] as inputs in the SD model and validation of the SD model outcomes with the projected GHG emission reductions reported by Le Den et al. [5]. Although the time horizon to 2050 does not fully incorporate the recycling of ARPs with the longest average lifespan (60 years for Building and Construction), this does not affect the SD model outcomes because the SD model uses moving averages in the simulation. The timestep used for the simulation runs is 1/8 year, which is smaller than the smallest time constant of the SD model, which is 1 year [23]. Preliminary experiments reveal no differences in results between the Runge Kutta and Euler integration methods. Runge Kutta and Euler integration both have advantages and disadvantages. For example, the Euler integration method assumes that rates remain the same over the entire time interval, while Runge Kutta uses a better approximation of the average rate for a time interval. However, Runge Kutta requires more computational time than Euler integration [23]. Since the Euler integration method is more accurate than the Runge Kutta method when a model incorporates discontinuous elements, such as step functions and the implementation of policies [23], the Euler integration method has been adopted in the current research.

The SD model presents the supply chain, demand evolutions, decarbonization technologies, and economic and environmental development. The variables that are expected to influence the chosen model boundary are included in the SD model. To ensure that the endogenous content of the SD model fits the boundaries for boundary adequacy validation [23,76], partial model tests were conducted. In line with structure confirmation and parameter confirmation [23,76], industry experts and the literature were consulted to fit feedback relationships and to ensure the model mimicked the real system.

The behavior reproduction test validates whether the model behavior is consistent with available variable-specific data and similar predictions [23], and therefore, partial model tests are performed. The model output shows an almost linear growth for European ARP demand until 2050 (see Figure 3). The linear growth from 2020 to 2050 is cross-validated as an out-of-sample test with industry experts and literature. This growth pattern is validated and found to be consistent with similar predictions found in the literature [45,77] and was confirmed in an extensive consultation with industry experts, analysts, and academics [8].

Theil inequality statistics evaluate the fit between observed and simulated data [23]. Theil inequality statistics decompose the mean square error (MSE) into three components: bias (UM), unequal variation (US), and unequal covariation (UC). The three components always sum to 1. Theil inequality statistics have been used to evaluate the correct modeling fit for primary aluminum production with historical data from 1990 to 2020 obtained from IAI [61]. Figure 5 shows the simulated and historic data on which the Theil statistics are based. The results show a low bias of UM = 0.0026 and a variance concentrated around the unequal variation of US = 0.6529 and an unequal covariation of UC = 0.3445 for the model variables. This indicates a good fit between the model outcome and the historical data. The high unequal variation US is caused by the implementation of an exponential function in the long run in the SD model versus disturbances in production in the real world in specific years. The deviations between simulated and actual behavior, known as noise, do not deteriorate the validity of the SD model [23]. For the other variables in the model, there are no detailed historical annual data available to conduct a similar, formal validation analysis. The overall model structure and results have, however, been validated by industry experts.

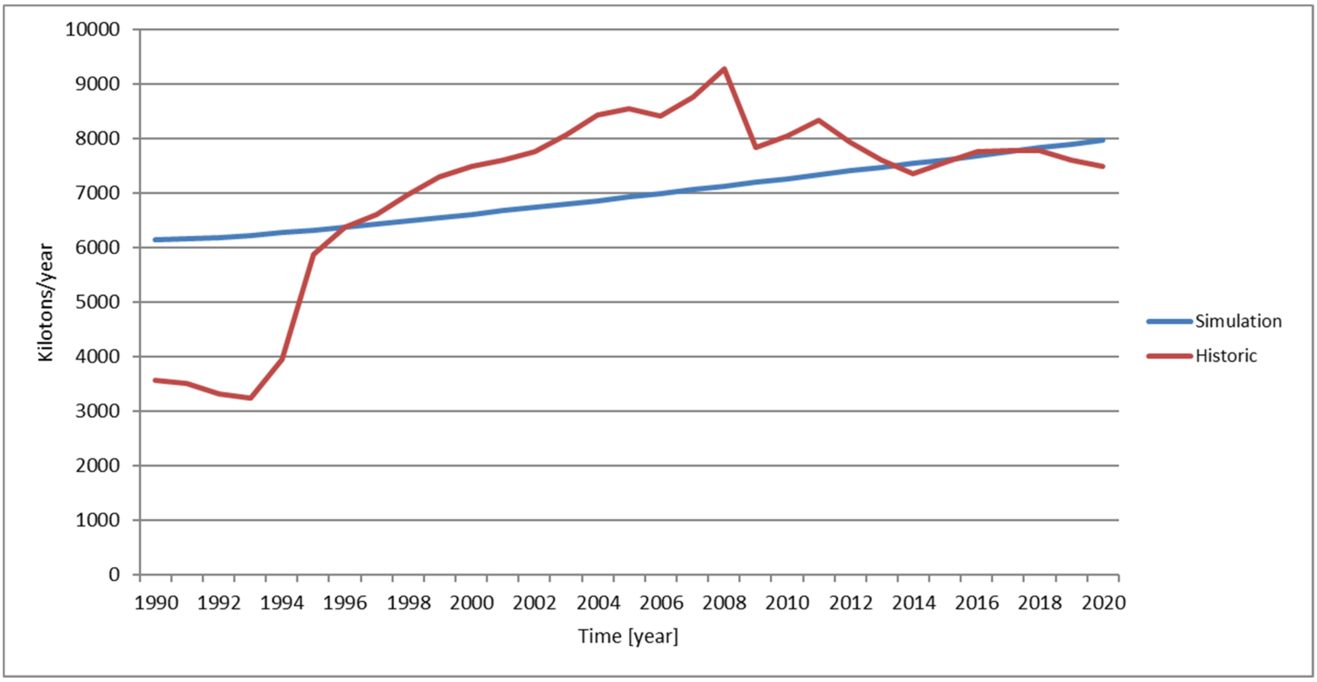

Figure 5. Simulated and historic data for primary aluminum production from 1990 to 2020 for Theil statistics.

5. Results

5.1. Scenario Development

Four scenarios are formulated to examine how demand and supply dynamics, environmental variables, and economic variables will affect achieving the European Green Deal's goal of zero net GHG emissions by 2050. The scenarios are based on the decarbonization pathways defined by the research commissioned by EA [5] and the implementation of decarbonization technologies by WEF [78]. The research commissioned by EA [5] was developed with the involvement of many industry partners to ensure the viability of the required investments and technologies. The expected capital investments per decade for each SC actor are also based on the research commissioned by EA [5]; they start in 2021 and end in 2050. Decarbonization technologies are assumed to become commercially viable at the start of each decade.

Collaboration and joint action between ARPSC actors are required to ensure successful and rapid decarbonization [78]. Therefore, Scenarios 1 to 4 test the effect of different investment strategies in different decades for different SC actors on the decarbonization of the ARPSC. Table 3 provides an overview of the different scenario parameters and their associated adoption trends for capital investments in decarbonization technologies by Upstream Supply Chain (USC) and Downstream Supply Chain (DSC) actors.

Table 3. Overview of the scenarios and related model variables for upstream (USC) and downstream supply chain (DSC) partners assessed with the SD model.

Scenario	Scenario Definition	Sub Scenario	Demand Growth	Supply Drivers					
				2021–2030		2031–2040		2041–2050	
				USC	DSC	USC	DSC	USC	DSC
0	Base scenario		As forecasted by the model	No investments					
1	Constant adoption of decarbonization technologies			Constant	Constant	Constant	Constant	Constant	Constant
2	Slow adoption of decarbonization technologies			Slow	Slow	Slow	Slow	Slow	Slow
3	Fast adoption of decarbonization technologies			Fast	Fast	Fast	Fast	Fast	Fast
4	Different adoption speeds of decarbonization technologies	4.1		Slow	Fast	Slow	Fast	Slow	Fast
		4.2		Fast	Slow	Fast	Slow	Fast	Slow
		4.3		Slow	Slow	Fast	Fast	Slow	Slow
		4.4		Fast	Fast	Slow	Slow	Fast	Fast

To analyze the effect of different investment strategies for different SC actors in different decades on GHG emissions for the European ARPSC, the following scenarios are formulated based on the adoption trends in Figure 4. Historical investment patterns in the European ARPSC were not as extensive as the currently proposed investments in decarbonization technologies. The current state of the European ARPSC, as also pointed out by the European Commission [79], requires unprecedented investments in decarbonization technologies to meet the European Green Deal goals. Unprecedented investments require the development of new scenarios. Scenarios 1 to 3 assume that the chosen adoption trend is applied to each decade for all ARPSC actors. Scenario 1 considers a constant adoption trend of decarbonization technologies for upstream and downstream ARPSC actors every decade. Scenario 2 assumes a slow adoption, and Scenario 3 assumes a fast adoption of decarbonization technologies for upstream and downstream ARPSC actors every decade. To deepen the findings of Scenarios 1 to 3, Scenario 4 assesses the impact of different adoption trends in different decades for the upstream and downstream ARPSC actors in multiple sub-scenarios to illustrate the benefits of tailoring sustainability initiatives. The sub-scenarios deviate between the slow and fast adoption of implementing decarbonization technologies over different decades and different ARPSC actors. It is assumed that, regardless of the adoption trend, approximately €33 billion is invested in each scenario over a 30-year horizon [5]. USC actors are expected to cover more than 90% of this amount. It is also assumed that 67% of the capital investments will occur between 2031 and 2040 [5]. To address the fact that decarbonization technologies may not be operational immediately after investment, sensitivity tests are conducted. The first sensitivity test examines the impact of a lower effectiveness of the proposed investments. The second sensitivity test considers that the technology is not commercially viable at the beginning of each decade, but only starts 2 years after the beginning of the decade.

5.2. Scenario Analysis

5.2.1. Validation of Analysis Outcomes

To examine the impact of multiple sustainability pathways for the ARPSC actors, Scenarios 1 to 4 are compared to the Business-As-Usual (BAU) scenario using system dynamics modeling. BAU, hereafter referred to as Scenario 0, represents the situation in which ARPSC actors invest at a pace similar to that observed in historical data in decarbonization technologies. In Scenario 0, the demand for aluminum exhibits a steady growth similar to the expectations outlined by European Aluminum [55]. This results in an increase in the volume of low-carbon and high-carbon aluminum produced over time. Consequently, the GWP will increase by 238% from 1990 to 2050. Moreover, as illustrated in Figure 6, the cumulative BAU emissions from 2020 to 2050 will exceed the carbon budgets for European aluminum production from 2020 to 2050 of 339 $MtCO_2eq$ [5] by 198% by 2050. The carbon budgets for European aluminum production from 2020 to 2050 will be exceeded between 2036 and 2037 already. Business cannot continue as usual (see Figure 6) if the goal of remaining below a 1.5 °C temperature increase is to be achieved.

Besides presenting the BAU, Figure 6 has the purpose of illustrating the effects of investing in decarbonization technologies with different adoption trends compared to BAU. An analysis of Scenarios 1 to 3 indicates that the largest reductions in GWP over time can be achieved by a fast implementation of decarbonization technologies (Scenario 3) compared to a slow implementation (Scenario 2). However, the European aluminum industry will not be able to remain within the carbon budgets for European aluminum production from 2020 to 2050 of 339 $MtCO_2eq$ for aluminum production in Europe, even if investments follow a fast adoption trend (Scenario 3) (See Figure 6). A fast implementation of investments in decarbonization technologies (Scenario 3) exceeds the carbon budgets for European aluminum production from 2020 to 2050 [5] by approximately 7.7% by 2050, compared to 19.0% for a constant adoption trend (Scenario 1) and 28.7% for a slow adoption trend (Scenario 2). To illustrate, a slow adoption (Scenario 2) exceeds the carbon budgets for European aluminum production from 2020 to 2050 between 2037 and 2038, whereas a constant adoption (Scenario 1) exceeds the carbon budgets between 2039 and 2040 and the fast adoption (Scenario 3) even later between 2042 and 2043. Thus, even though the carbon budgets are exceeded in all scenarios, the impact of limiting the temperature increase to 1.5 °C above pre-industrial levels is smallest for the fast adoption (Scenario 3). These results confirm the observations of Le Den et al. [5], but they do not indicate the effect of different investment strategies across different decades and different SC actors on GHG emissions. However, it should be noted that the longer investments are delayed, the more mature the related technologies will be, which may impact the associated GHG emission reductions.

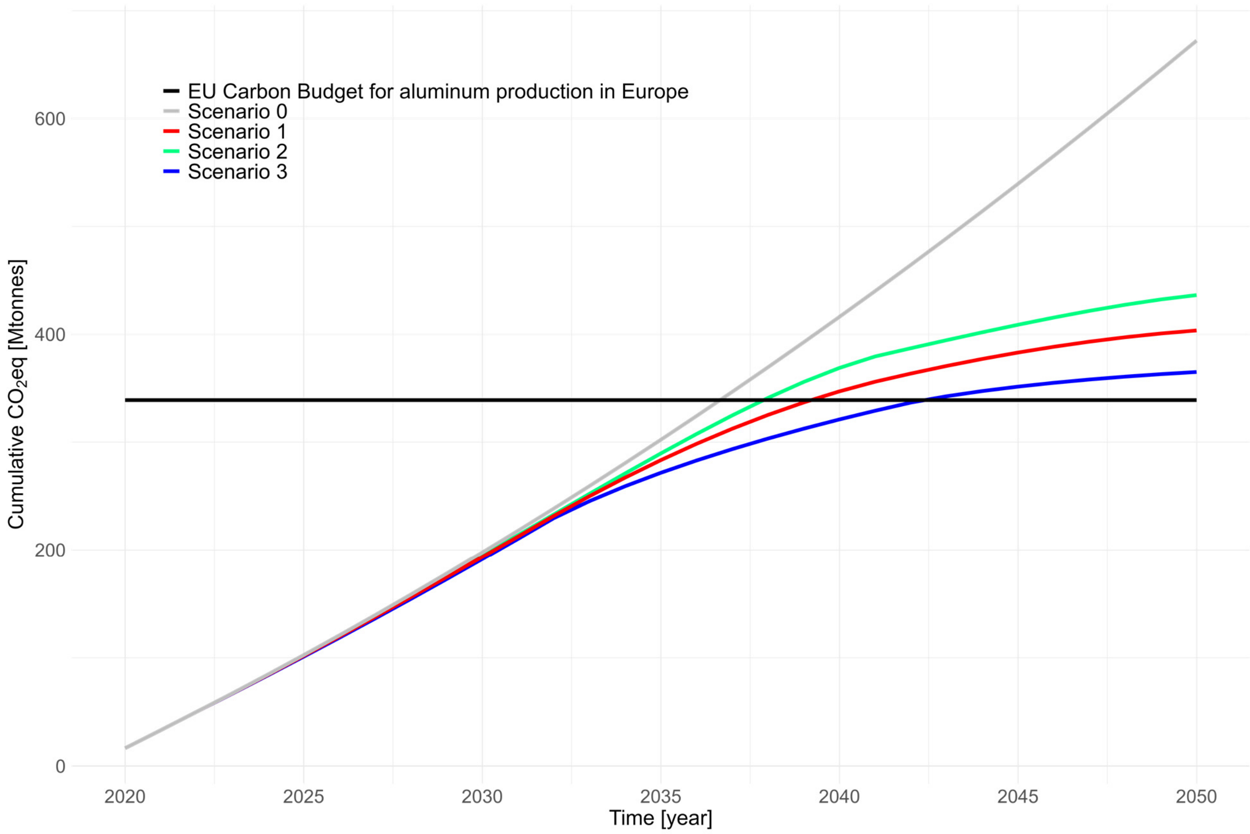

Figure 6. Accumulated GWP from European ARP production for Scenarios 0 to 3 compared to the cumulative carbon budgets for European aluminum production from 2020 to 2050.

5.2.2. Alternating Investment Speeds across Decades

Scenarios 4.1 to 4.4 analyze the effect of different investment strategies for different decades and different SC actors on GHG emissions. The purpose of Figure 7 is to show the effect of different investment strategies for different decades and different SC actors. Figure 7 indicates that the speed of investment between 2031 and 2040 is most decisive in the contribution to the accumulated GWP towards 2050, as two-thirds of the total investments are expected to occur between 2031 and 2040. Between 2021 and 2030, the implementation of decarbonization technologies mainly consists of a shift to electric boilers [5], which can be best illustrated by either a slow (Scenario 4.3) or fast (Scenario 4.4) adoption trend by both USC and DSC actors. However, a comparison of the two scenarios reveals only a small differentiation of 1.6% in the accumulated GWP by 2030. The implementation of electric furnaces between 2031 and 2040, according to slow (Scenario 4.3) and fast (Scenario 4.4) adoption trends, leads to a substantially larger difference in the accumulated GWP of 12.4% by 2040. This time, however, the most substantial reduction in accumulated GWP can be attributed to Scenario 4.3 rather than Scenario 4.4, as it considers a fast adoption trend compared to a slow one. The difference in the accumulated GWP between Scenarios 4.3 and 4.4 decreases again towards 2050 with the implementation of inert anodes [5], falling to 5.6% by 2050. Although a difference of 5.6% seems negligible, every percentage towards meeting the European Green Deal goals is important in reducing the global temperature increase. Scenario 4.3 exceeds the carbon budgets for European aluminum production from 2020 to 2050 between 2041 and 2042. Scenario 4.2 exceeds the carbon budgets between 2040 and 2041, whereas both Scenarios 4.1 and 4.4 exceed the carbon budgets between 2038 and 2039. In all cases, this is still later than Scenario 0 and contributes to reducing the global temperature increase. Moreover, a more effective reduction in the GWP may help policymakers implement extra policies to meet the EU requirements. The results of Sections 5.2.1 and 5.2.2 confirm the observations of Le Den et al. [5] and indicate that investment in decarbonization technologies alone, regardless of the chosen investment strategy, is not sufficient for the European ARPSC to remain within the carbon budgets for European aluminum production from 2020 to 2050.

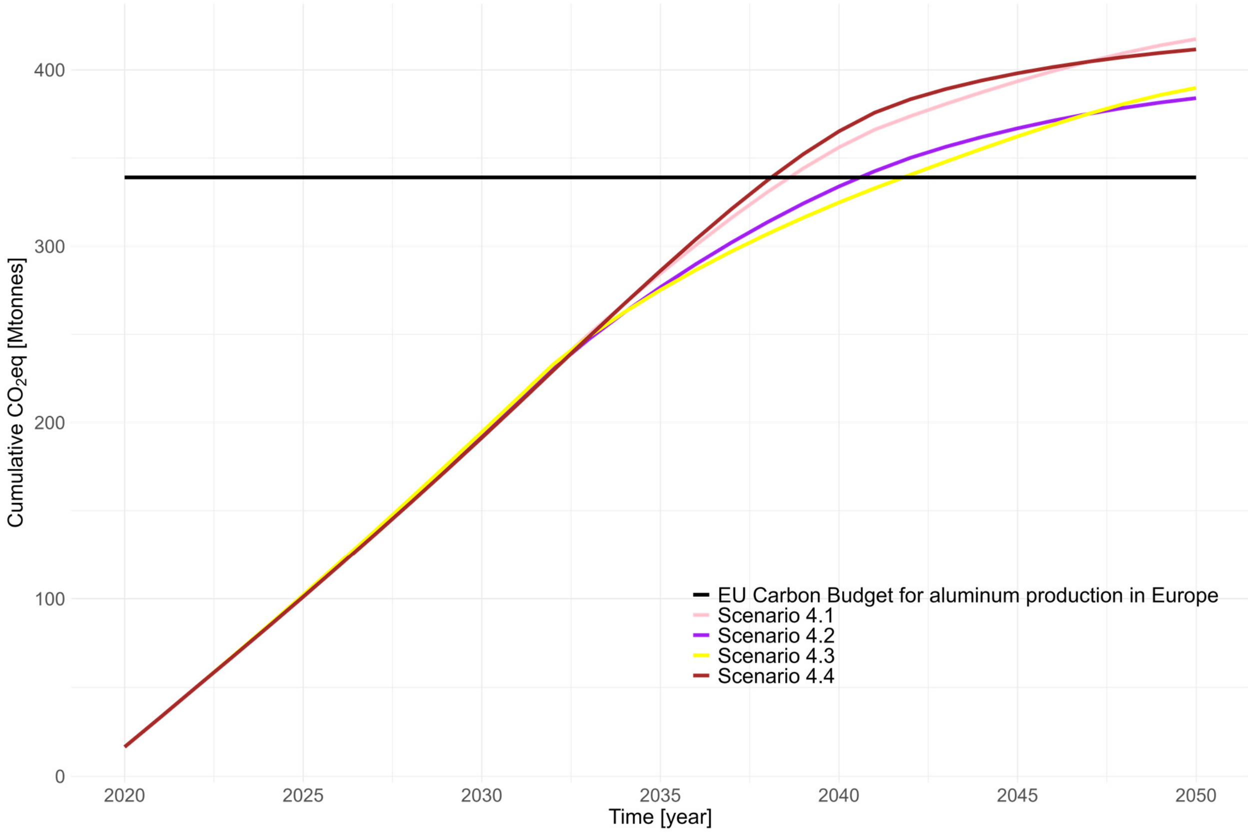

Figure 7. Accumulated GWP evolution of the European ARP production for Scenario 4 (different adoption trends in different decades for the upstream and downstream APRSC actors) compared to the carbon budgets for European aluminum production from 2020 to 2050.

5.2.3. Sensitivity Analysis

The SD model generates insight by evaluating and quantifying policies. To test the robustness and sensitivity of the model, two sensitivity tests are performed. These sensitivity tests are performed on top of Scenario 3 because this scenario achieves the largest GWP reduction by 2050. Sensitivity test 1 considers that the reduction in emissions for each intermediary product is 10% less effective than expected. The second sensitivity test considers that new technologies may not be commercially viable at the beginning of each decade, and therefore, the introduction is delayed by 2 years.

Figure 8 indicates that if a decarbonization technology turns out to be 10% less effective, it does not mean that the accumulated GWP is 10% higher than the results of Scenario 3. By 2050, the cumulative GWP is only 8.42% higher than in Scenario 3. A delay of 2 years has a greater impact on the accumulated GWP. A delay of 2 years results in an 11.43% increase in accumulated GWP by 2050 compared to Scenario 3. These sensitivity tests indicate that joint action and fast implementation of decarbonization technologies are of great value in achieving the European Green Deal goals. This is in line with the findings of Le Den et al. [5] and the European Commission [79], which emphasize that decarbonization is a joint effort of multiple stakeholders and therefore has a stronger effect on the GWP.

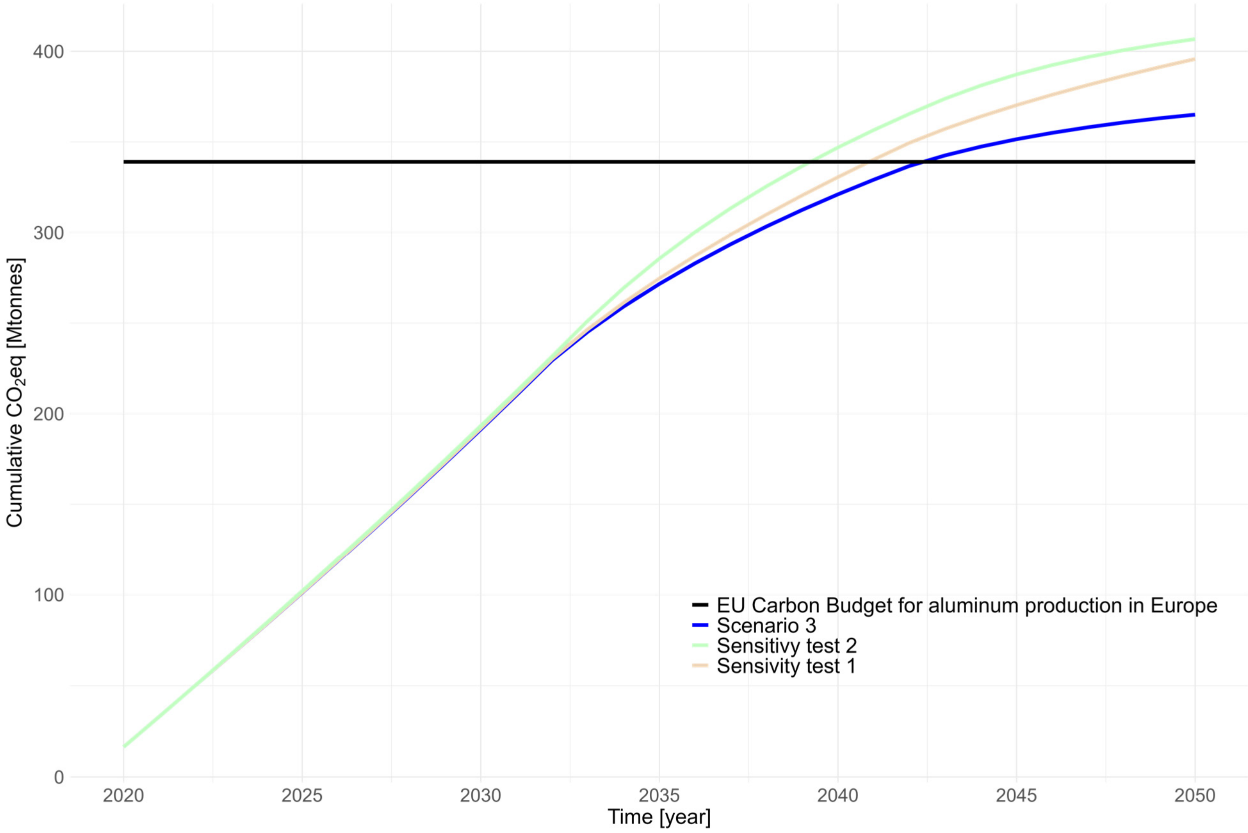

Figure 8. Accumulated GWP evolution of the European ARP production for Scenario 3 and two different sensitivity tests compared to the carbon budgets for European aluminum production from 2020 to 2050.

5.2.4. Sustainable Production and Consumption

As demonstrated in the previous subsections, investments in decarbonization technologies alone are not sufficient for the European ARPSC to remain within the carbon budgets for European aluminum production from 2020 to 2050. Therefore, additional policies are required. The SD model can be used to generate new insights by evaluating and quantifying additional strategies to further reduce emissions in the European ARPSC, while remaining within the carbon budgets for European aluminum production between 2020 and 2050. To illustrate this, two scenarios on sustainable production and consumption are considered. The recycling scenario tests the effect of enhanced circularity in the form of optimized recycling and the resource sufficiency scenario tests the effect of increased resource sufficiency through the sharing or reuse of products, often referred to as resource sufficiency. Resource sufficiency aims to lower resource consumption and its associated impact [80]. The scenario values for each sector are presented in Table 4. These two scenarios are performed as an extension of Scenario 3, as this scenario achieves the largest GWP reduction by 2050.

Table 4. Simulation values of scenarios to support sustainable production and consumption.

Sector \ Scenario	Recycling	Resource Sufficiency
Automotive industry	Gradual increase from 50% recycling in 2020 to 80% recycling in 2050 [6]	Car sharing increases gradually from 1.3% [53] in 2020 to 2.9% in 2029 [81–83]. Comparable growth is anticipated between 2029 and 2050, reaching a projected 6.1% in 2050.
Packaging	Gradual increase from 50% recycling in 2020 to 80% recycling in 2050 [6]	Using multiple-use packaging increases gradually from 0% in 2020 to 25% [84,85] in 2050.
Building and Construction	Gradual increase from 50% recycling in 2020 to 80% recycling in 2050 [6]	-

The recycling scenario tests the effect of a higher aluminum recycling rate. Recycling is expected to increase from approximately 50% to 80% over the next three decades, from 2020 to 2050 [6], thereby increasing circularity for all sectors. The results of the model indicate that a higher recycling rate for all product sectors would result in a reduction in accumulated CO_2eq emissions from 2020 to 2050 by 3.71% in 2050 compared to Scenario 3 (see Figure 9). Despite the efforts to recycle more products, the accumulated emissions remain above the carbon budgets for European aluminum production from 2020 to 2050. The carbon budget is exceeded by 3.69%, which is approximately half of the budget excess in Scenario 3.

The resource sufficiency scenario tests the effect of sharing cars and using packaging more than once. It is assumed that aluminum in the building and construction sector cannot be shared or used multiple times without first being recycled. Sharing cars and using packaging multiple times, such as aluminum bottles [86], reduces the overall demand for ARP. As the demand for ARP falls, the production of ARP is reduced. Even though the implementation of this scenario is not capable of meeting the carbon budgets for European aluminum production from 2020 to 2050, the accumulated CO_2eq emissions are reduced by a further 4.71% by 2050 compared to Scenario 3 alone (see Figure 9). In fact, resource sufficiency reduces the accumulated CO_2eq emissions more than the recycling scenario because it directly reduces demand rather than the need for primary resources.

The individual scenarios for increased recycling and resource sufficiency show a decrease in GHG emissions in the period leading up to 2050 compared to Scenario 3. However, none of the individual scenarios allow the industry to remain below the carbon budgets for European aluminum production from 2020 to 2050. Figure 9 shows that a combination of both scenarios in addition to Scenario 3 is the only means of remaining below the carbon budgets for European aluminum production from 2020 to 2050. The two combined scenarios result in a further decrease in accumulated CO_2eq emissions by 8.19% by 2050 compared to Scenario 3 alone. This result indicates that policies related to recycling and the sharing of products or reusable products strongly influence the projected levels of associated GHG emissions for the European ARPSC.

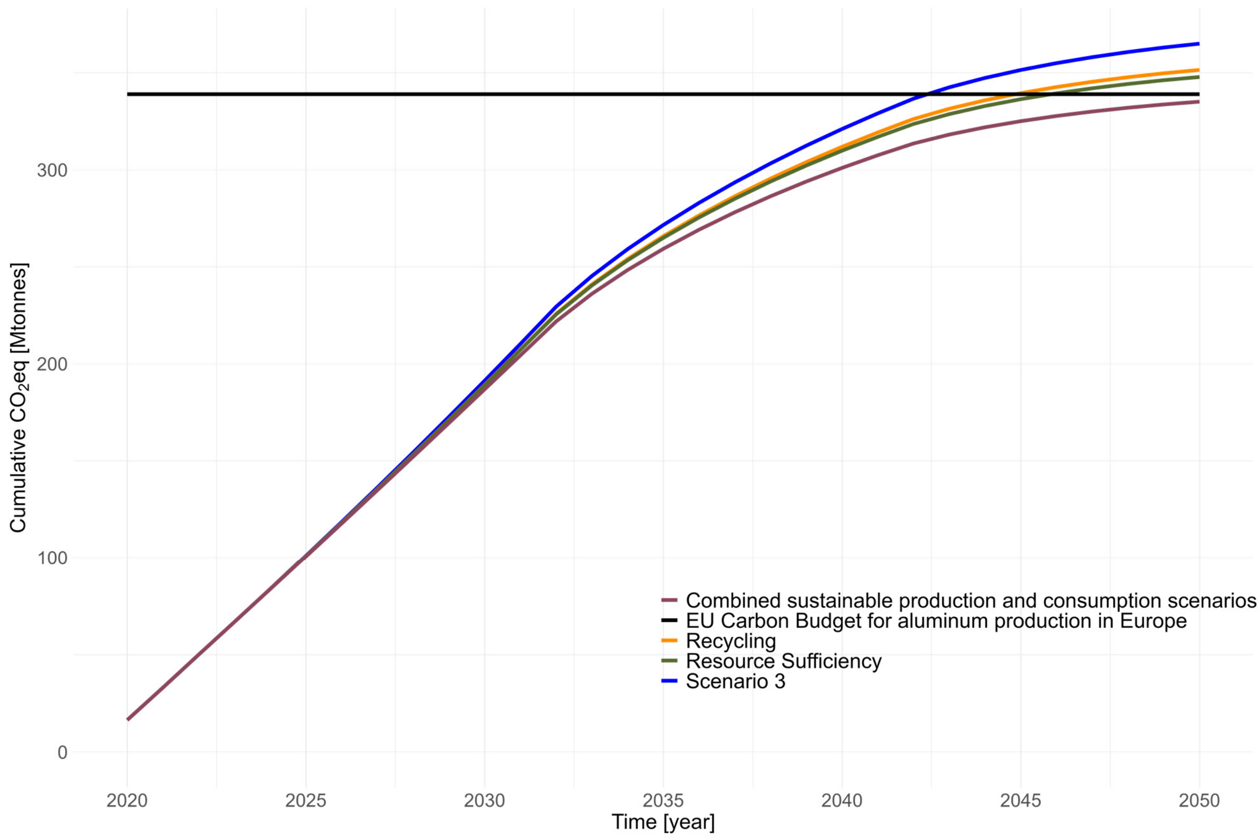

Figure 9. Analysis of the accumulated GWP evolution of the European ARP production for the scenarios to support sustainable production and consumption, in addition to Scenario 3 compared to the carbon budgets for European aluminum production from 2020 to 2050.

6. Conclusions

The dynamics between demand and supply, technological developments, government regulations, and environmental and economic objectives are relevant elements for SSCs [11]. Transitioning towards an SSC is particularly challenging for energy-intensive industries [3], like the aluminum industry. The European aluminum industry needs to reduce GHG emissions to achieve the targets set by the European Green Deal [2] while safeguarding profitability under the increasing capital expenditure costs for implementing new decarbonization technologies.

Previous research [10,12–16] covers important elements for the transition to an SSC. However, none of the current literature examines the combination of supply and demand evolutions in SSCs with environmental and economic variables, government regulations, and sustainable adoption trends in a single model, which is important for achieving the European Green Deal goals by 2050. Moreover, the impact of interactions between supply chain actors while considering environmental constraints on economic activities is underexplored.

To address these research gaps and contribute to existing literature, this paper presents a comprehensive system dynamics (SD) model, which integrates the evolution of demand and supply of primary and secondary resources in combination with investments for different decarbonization technologies, environmental impacts, applicable EU government regulations, and sustainable adoption trends. The research examines the impact of different investment strategies in decarbonization technologies for the European Aluminum Rolled Products Supply Chain (APRSC) to meet the European Green Deal goals by 2050 while simultaneously meeting the expected growth in European demand for low-carbon Aluminum Rolled Products (ARPs). Moreover, it quantifies the scenarios to support stakeholders in strategic decisions to limit global warming and identify the impact on individual supply chain partners.

A recent study commissioned by European Aluminum and conducted by Le Den et al. [5] is used as the input for the SD model and to validate our SD model outcomes. Extensive scenario analysis with the SD model indicates that investments in decarbonization technologies by both upstream and downstream ARPSC actors have the potential to substantially reduce the global warming potential (GWP). However, the planned investments that have been announced will not reduce the GWP sufficiently to align with the carbon budgets for European aluminum production from 2020 to 2050. Therefore, the SD model generates several additional insights to complement these observations by simulating different investment strategies for different decades and different SC actors. More specifically, the SD model scenario analysis indicates that a fast investment between 2031 and 2040 by upstream ARPSC actors will have the greatest impact on reducing the GWP for the European ARPSC. Moreover, a fast implementation results in a greater reduction in the accumulated GWP for European production by 2050 than a slow implementation. Investments in decarbonization technologies do delay the moment that the carbon budgets for European aluminum production from 2020 to 2050 are exceeded. However, with all investment strategies, the accumulated GWP for European production exceeds the carbon budgets for European aluminum production from 2020 to 2050, suggesting the necessity for additional measures beyond the implementation of decarbonization technologies. Increasing sustainable production and consumption in the supply chain in the form of increasing the rate of recycling and resource sufficiency results in a further reduction in the GWP of the European ARPSC. However, in order to reach the carbon budgets for European aluminum production from 2020 to 2050, a combination of these two strategies must be used in addition to a fast adoption of decarbonization technologies.

The study can help practitioners and policymakers by quantifying the impact of sustainability investments and targets, highlighting the need for supply chain alignment and collaboration. As the investment costs and the impact on the entire supply chain GWP differ for each supply chain actor, the supply chain actors need to collaborate to obtain the best possible outcomes to achieve the Green Deal goals by 2050 and possibly spread costs across the supply chain. However, it should be noted that there are barriers to investing in supply chain decarbonization, such as major upfront investment costs, climate uncertainty [87], a lack of awareness, and a lack of expertise. Moreover, SMEs face an additional lack of support from supply chain partners and uncertainty about the return on investment [88]. Moreover, without good policy intervention, the incentive to decarbonize can be more pessimistic similar to the decarbonization of big companies in Japan, which is considered challenging [89]. The degree of competitiveness of a supply chain and the degree of bilateral decisions impact the investment strategies for decarbonization [90]. Factors, such as delayed learning about the carbon budget after, for example investing in decarbonization technologies between 2021 and 2030, may impact the post-2030 spending, which might increase the overall policy costs for decarbonizing the supply chain [87]. At the European level, Mario Draghi stated in his report "The future of European competitiveness" that the coordination of European policies on sustainability, competitiveness, and growth is a prerequisite for Europe's decarbonization [79]. Europe is currently the world's recycling champion, but according to the EEA [91], the ambition to double the Union's circularity rate by 2030 is under pressure from the current rate of progress. To support the leading ambition in realizing the circular economy, environmental taxation has the potential to play a key role in realizing a shift towards a sustainable, decarbonized economy [92]. This study also contributes to the operations management literature by simultaneously addressing the dynamic interactions between demand and supply evolutions, EU government regulations, sustainable adoption trends, investments for different decarbonization technologies, environmental requirements, and economic components. First, by modeling these interactions in combination with potential decarbonization pathways towards sustainability, our results can be used to support strategic decision-making in the European ARPSC to indicate the required investments and the impact on the environment for decarbonization technologies and specific ARPSC actors. Second, although the SD model is complex, it is flexible in terms of adding additional feedback loops and can serve as a springboard to analyze specific investment strategies, e.g., different decarbonization technologies and sustainability challenges in other (metal) supply chains.

Due to the scope of this research, the focus of the proposed SD model is currently limited to the implementation of different decarbonization technologies in Europe in the context of demand and supply evolutions to examine their economic and environmental impacts. At present, the model does not incorporate social factors that may influence the production process and demand for low-carbon aluminum. Moreover, the SD model relies on the continuation of averages in historical data. The effect of possible disruptions in the system related to the implementation of decarbonization technology in the future is not considered. The investment data for decarbonization technologies used in the model do not take into account the different interests and investment budgets of the different supply chain actors. This may lead to lopsided growth and thus in a different reduction in GWP than expected. In addition, the SD model assumes that any decarbonization technology becomes operational immediately after investment. In real-life, it is likely that some time will pass before a new technology is fully operational. As there is currently no specific data on the duration of such implementations, the operationability had to be simplified in the current model. Further research efforts may be aimed at relaxing some of the research limitations mentioned above. For example, the system boundaries of this research can be extended by incorporating social factors, such as the employment impact or community resistance to technological change. Moreover, the implementation of additional policies, such as the implementation of stricter carbon pricing, is interesting to explore additional ways to limit the GWP.

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References

1. United Nations. Paris Agreement. 2015. Available online: https://unfccc.int/sites/default/files/english_paris_agreement.pdf (accessed on 15 April 2022).
2. European Commission. The European green deal. *Eur. Comm.* **2019**, *53*, 24.
3. IEA. *Tracking Clean Energy Progress 2023*; IEA: Paris, France, 2023. Available online: https://www.iea.org/reports/tracking-clean-energy-progress-2023 (accessed on 9 October 2024).
4. Seuring, S.; Müller, M. From a literature review to a conceptual framework for sustainable supply chain management. *J. Clean. Prod.* **2008**, *16*, 1699–1710. [CrossRef]
5. Le Den, X.; Caspani, M.; Bey, N.; Marton, C.; Sveistrup Holck, K.; Janin Mayr, N. Science-Based Decarbonisation Pathways Decarbonisation Pathways European Aluminium Industry. 2023. Available online: https://european-aluminium.eu/wp-content/uploads/2023/11/23-11-14-Net-Zero-by-2050-Science-based-Decarbonisation-Pathways-for-the-European-Aluminium-Industry_FULL-REPORT.pdf (accessed on 9 October 2024).
6. Gregoir, L.; van Acker, K. Metals for Clean Energy: Pathways to Solving Europe's Raw Materials Challenge. Eurometaux, KU Leuven. 2022. Available online: https://eurometaux.eu/media/20ad5yza/2022-policymaker-summary-report-final.pdf (accessed on 9 October 2024).
7. BIR (Bureau of International Recycling). Report on Environmental Benefits of Recycling. 2008. Available online: https://www.mgg-recycling.com/wp-content/uploads/2013/06/BIR_CO2_report.pdf (accessed on 8 May 2020).
8. IAI. An Assessment of Global Megatrends and Regional and Market Sector Growth Outlook for Aluminium Demand. 2020. Available online: https://international-aluminium.org/wp-content/uploads/2021/03/cm_2050_outlook_for_al_demand_20200528_4wycD18.pdf/ (accessed on 11 May 2022).
9. Lu, F.; Hao, H.; Bi, H. Evaluation on the development of urban low-carbon passenger transportation structure in Tianjin. *Res. Transp. Bus. Manag.* **2024**, *55*, 101142. [CrossRef]
10. Pinto, J.T.; Diemer, A. Supply chain integration strategies and circularity in the European steel industry. *Resour. Conserv. Recycl.* **2020**, *153*, 104517. [CrossRef]
11. Rebs, T.; Brandenburg, M.; Seuring, S. System dynamics modeling for sustainable supply chain management: A literature review and systems thinking approach. *J. Clean. Prod.* **2019**, *208*, 1265–1280. [CrossRef]
12. Zimon, D.; Tyan, J.; Sroufe, R. Drivers of sustainable supply chain management: Practices to alignment with unsustainable development goals. *Int. J. Qual. Res.* **2020**, *14*, 219–236. [CrossRef]
13. Sharifi, E.; Fang, L.; Amin, S.H. A novel two-stage multi-objective optimization model for sustainable soybean supply chain design under uncertainty. *Sustain. Prod. Consum.* **2023**, *40*, 297–317. [CrossRef]
14. Zahraee, S.M.; Golroudbary, S.R.; Shiwakoti, N.; Kraslawski, A.; Stasinopoulos, P. An investigation of the environmental sustainability of palm biomass supply chains via dynamic simulation modeling: A case of Malaysia. *J. Clean. Prod.* **2019**, *237*, 117740. [CrossRef]
15. Guo, Y.; Yu, Y.; Ren, H.; Xu, L. Scenario-based DEA assessment of energy-saving technological combinations in aluminum industry. *J. Clean. Prod.* **2020**, *260*, 121010. [CrossRef]
16. Sverdrup, H.U.; Ragnarsdottir, K.V.; Koca, D. Aluminium for the future: Modelling the global production, market supply, demand, price and long term development of the global reserves. *Resour. Conserv. Recycl.* **2015**, *103*, 139–154. [CrossRef]
17. Seuring, S. A review of modeling approaches for sustainable supply chain management. *Decis. Support Syst.* **2013**, *54*, 1513–1520. [CrossRef]
18. Curran, M.A. Life cycle assessment: A review of the methodology and its application to sustainability. *Curr. Opin. Chem. Eng.* **2013**, *2*, 273–277. [CrossRef]
19. Paul, A.; Shukla, N.; Paul, S.K.; Trianni, A. Sustainable supply chain management and multi-criteria decision-making methods: A systematic review. *Sustainability* **2021**, *13*, 7104. [CrossRef]
20. Boulanger, P.M.; Bréchet, T. Models for policy-making in sustainable development: The state of the art and perspectives for research. *Ecol. Econ.* **2005**, *55*, 337–350. [CrossRef]
21. Inghels, D.; Dullaert, W.; Raa, B.; Walther, G. Influence of composition, amount and life span of passenger cars on end-of-life vehicles waste in Belgium: A system dynamics approach. *Transp. Res. Part A Policy Pract.* **2016**, *91*, 80–104. [CrossRef]
22. Honti, G.; Dörgő, G.; Abonyi, J. Review and structural analysis of system dynamics models in sustainability science. *J. Clean. Prod.* **2019**, *240*, 118015. [CrossRef]
23. Sterman, J. *Business Dynamics*; McGraw-Hill, Inc.: Chicago, IL, USA, 2000.
24. Doyle, J.K.; Ford, D.N. Mental models concepts for system dynamics research. *Syst. Dyn. Rev. J. Syst. Dyn. Soc.* **1998**, *14*, 3–29. [CrossRef]
25. Halog, A.; Manik, Y. Advancing integrated systems modelling framework for life cycle sustainability assessment. *Sustainability* **2011**, *3*, 469–499. [CrossRef]
26. Towill, D.R. Industrial dynamics modelling of supply chains. *Logist. Inf. Manag.* **1996**, *9*, 43–56. [CrossRef]
27. Mingers, J.; White, L. A review of the recent contribution of systems thinking to operational research and management science. *Eur. J. Oper. Res.* **2010**, *207*, 1147–1161. [CrossRef]
28. Bankes, S.; Walker, W.E.; Kwakkel, J.H. *Exploratory Modeling and Analysis*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 532–537.

29. Meadows, D.H.; Meadows, D.L.; Randers, J.; Behrens, W.W., III. *The Limits to Growth—A Report for the Club of Rome's Project on the Predicament of Mankind*; Universe Books: New York, NY, USA, 1972.
30. Meadows, D.H.; Randers, J. Limits to Growth: The 30-Year Update. *Política y Sociedad.* **2006**, *43*, 213–216.
31. Randers, J. *2052: A Global Forecast for the Next Forty Years: A Report to the Club of Rome Commemorating the 40th Anniversary of "The Limits to Growth"*; Chelsea Green Publishing: White River Junction, VT, USA, 2012.
32. Dixson-Declève, S.; Gaffney, O.; Ghosh, J.; Randers, J.; Rockstrom, J.; Stoknes, P.E. *Earth for All: A Survival Guide for Humanity*; A Report to the Club of Rome; New Society Publishers: Gabriola Island, BC, Canada, 2022.
33. United Nations. General Assembly; Transforming Our World: The 2030 Agenda for Sustainable Development. 2015. Available online: https://documents.un.org/doc/undoc/gen/n15/291/89/pdf/n1529189.pdf (accessed on 3 October 2024).
34. U.S. Government. Public Law 117-169; 117th Congress. 2022. Available online: https://www.congress.gov/bill/117th-congress/house-bill/5376/text (accessed on 3 October 2024).
35. Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F.S., III; Lambin, E.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. Planetary boundaries—Exploring the safe operating space for humanity. *Ecol. Soc.* **2009**, *14*, 32. [CrossRef]
36. European Commission. Net Zero Industry Act. 2023. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023PC0161 (accessed on 3 October 2024).
37. IEA. *Tracking Clean Energy Innovation Policies*; IEA: Paris, France, 2024. Available online: https://www.iea.org/reports/tracking-clean-energy-innovation-policies (accessed on 9 October 2024).
38. Suryani, E.; Hendrawana, R.A.; Muhandhisa, I.; Dewib, L.P. Dynamic simulation model of beef supply chain to fulfill national demand. *J. Teknol.* **2016**, *78*, 169–177. [CrossRef]
39. Aivazidou, E.; Tsolakis, N.; Vlachos, D.; Iakovou, E. A water footprint management framework for supply chains under low-carbon market behaviour. *J. Clean. Prod.* **2018**, *197*, 592–606. [CrossRef]
40. Sharma, V.; Raj, A.; Chakraborty, A. Analysis of power dynamics in sustainable supply chain under non-linear demand setup. *Oper. Manag. Res.* **2023**, *16*, 18–32. [CrossRef]
41. Gold, S.; Seuring, S.; Beske, P. Sustainable supply chain management and inter-organizational resources: A literature review. *Corp. Soc. Responsib. Environ. Manag.* **2010**, *17*, 230–245. [CrossRef]
42. Wang, G.; Gunasekaran, A. Modeling and analysis of sustainable supply chain dynamics. *Ann. Oper. Res.* **2017**, *250*, 521–536. [CrossRef]
43. European Aluminium. The Voice of the European Aluminium Industry. 2024. Available online: https://european-aluminium.eu/our41-team/ (accessed on 5 March 2024).
44. European Aluminium. Market Overview. 2019. Available online: https://www.european-aluminium.eu/activity-report-2019-2020/market-overview/ (accessed on 11 May 2022).
45. Watari, T.; Nansai, K.; Nakajima, K. Major metals demand, supply, and environmental impacts to 2100: A critical review. *Resour. Conserv. Recycl.* **2021**, *164*, 105107. [CrossRef]
46. Schipper, B.W.; Lin, H.C.; Meloni, M.A.; Wansleeben, K.; Heijungs, R.; van der Voet, E. Estimating global copper demand until 2100 with regression and stock dynamics. *Resour. Conserv. Recycl.* **2018**, *132*, 28–36. [CrossRef]
47. Eurostat. Population on 1 January. 2022. Available online: https://ec.europa.eu/eurostat/databrowser/view/tps00001/default/table?lang=en (accessed on 11 May 2022).
48. Eurostat. Real GDP Growth Rate—Volume. 2020. Available online: https://ec.europa.eu/eurostat/databrowser/view/tec00115/default/table?lang=en (accessed on 14 February 2020).
49. Statista. Number of Registered Passenger Cars in Europe (EU-28) from 1990 to 2017. 2020. Available online: https://www.statista.com/statistics/452447/europe-eu-28-number-of-registered-passenger-cars/ (accessed on 11 May 2022).
50. ACEA. EU Passenger Car Production. 2020. Available online: https://www.acea.be/statistics/article/eu-passenger-car-production/ (accessed on 11 May 2022).
51. DuckerFrontier. Aluminum content in European Passenger Cars. Public Summary. 2019. Available online: https://european-aluminium.eu/wp-content/uploads/2022/10/aluminum-content-in-european-cars_european-aluminium_public-summary_101019-1.pdf (accessed on 21 February 2023).
52. European Commission. Advanced Technologies for Industry. 2021. Available online: https://ec.europa.eu/growth/tools-databases/dem/monitor/tags/car-service/ (accessed on 11 May 2022).
53. BCG. What's Ahead for Car Sharing? The New Mobility and Its Impact on Vehicle Sales. 2016. Available online: https://www.bcg.com/publications/2016/automotive-whats-ahead-car-sharing-new-mobility-its-impact-vehicle-sales/ (accessed on 11 May 2022).
54. BPIE. 2015. Available online: http://bpie.eu/wp-content/uploads/2015/10/HR_EU_B_under_microscope_study.pdf/ (accessed on 2 October 2021).
55. European Aluminium. Vision 2050: A Vision for Strategic, Low Carbon and Competitive Aluminium. 2019. Available online: https://european-aluminium.eu/wp-content/uploads/2022/10/sample_vision-2050-low-carbon-strategy_20190401.pdf (accessed on 11 May 2022).
56. Technavio. Global Aluminum Market for Packaging Industry 2020–2024. 2020. Available online: https://www.businesswire.com/news/home/20200702005421/en/Global-Aluminum-Market-Packaging-Industry-2020-2024-Growing/ (accessed on 11 May 2022).

57. Alcircle. How Consumers Preference for Aluminium Cans Evolving Consumption and Recycle Pattern All over the World. 2019. Available online: https://blog.alcircle.com/2019/09/30/consumers-preference-aluminium-cans-evolving-consumption-recycle-pattern-world/ (accessed on 11 May 2022).
58. PKG. Eco-Friendly Packaging: What Consumers Really Want. 2017. Available online: https://www.pkgbranding.com/blog/eco-friendly-packaging-what-consumers-really-want (accessed on 11 May 2022).
59. IAI. The Lightness of Aluminium Packaging Helps to Save Resources during Filling, Product Transportation, Storage and the Transportation of Scrap at the End of a Product's Life. 2020. Available online: https://packaging.world-aluminium.org/benefits/lightweight/#:~:text=Today,%20cans%20can%20be%20produced,of%20aluminium%20globally%20per%20annum/ (accessed on 11 May 2022).
60. Klaiman, K.; Ortega, D.L.; Garnache, C. Consumer preferences and demand for packaging material and recyclability. *Resour. Conserv. Recycl.* **2016**, *115*, 1–8. [CrossRef]
61. IAI. Statistics of Aluminum Production. 2024. Available online: https://www.world-aluminium.org/statistics/#map/ (accessed on 12 January 2024).
62. European Aluminium. Environmental Profile Report. 2018. Available online: https://european-aluminium.eu/resource-hub/environmental-profile-report-2018/ (accessed on 11 May 2022).
63. Bertram, M.; Ramkumar, S.; Rechberger, H.; Rombach, G.; Bayliss, C.; Martchek, K.; Müller, D.; Liu, G. A regionally-linked, dynamic material flow modelling tool for rolled, extruded and cast aluminium products. *Resour. Conserv. Recycl.* **2017**, *125*, 48–69. [CrossRef]
64. Inghels, D. *Introduction to Modeling Sustainable Development in Business Processes—Theory and Case Studies*, 1st ed.; Hardcover; Springer International Publishing: Berlin/Heidelberg, Germany, 2020; 231p, ISBN 978-3-030-58421-4.
65. Buffington, J. The beverage can in the United States: Achieving a 100% recycled aluminum can through supply chain innovation. *JOM* **2012**, *64*, 923–932. [CrossRef]
66. Agoria. Role of the Industry in Achieving the Climate Objectives. 2019. Available online: https://www.agoria.be/en/Role-of-the-industry-in-achieving-the-climate-objectives/ (accessed on 11 May 2022).
67. European Commission. Carbon Leakage. 2020. Available online: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/free-allocation/carbon-leakage_en (accessed on 11 May 2022).
68. Free allocation Regulation (EU) 2019/331. Commission Delegated Regulation (EU) 2019/331 Determining Transitional Union-wide Rules for Harmonised Free Allocation of Emission Allowances Pursuant to Article 10a of Directive 2003/87/EC of the European Parliament and of the Council. 2019. Available online: https://eur-lex.europa.eu/eli/reg_del/2019/331/oj/ (accessed on 11 May 2022).
69. European Commission. Establishing the Framework for Achieving Climate Neutrality and Amending REGULATION (EU) 2018/1999 (European Climate Law). 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/%20PDF/?uri=CELEX:52020PC0080&%20from=EN/ (accessed on 11 May 2022).
70. European Commission. Carbon Border Adjustment Mechanism. (n.d.). Available online: https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en (accessed on 12 January 2023).
71. Hydro. Future-Proof, Greener Aluminium: Hydro REDUXA and Hydro CIRCAL. 2021. Available online: https://www.hydro.com/en/aluminium/products/low-carbon-aluminium/ (accessed on 11 May 2022).
72. Alcoa. Alcoa Expands Its Sustana^{TM} Family of Products with EcoSource^{TM}, the Industry's First Low-Carbon Alumina Brand. 2020. Available online: https://news.alcoa.com/press-releases/press-release-details/2020/Alcoa-Expands-its-SustanaTM-Family-of-Products-with-EcoSourceTM-the-Industrys-First-Low-Carbon-Alumina-Brand/default.aspx (accessed on 11 May 2022).
73. Geroski, P.A. Models of technology diffusion. *Res. Policy* **2000**, *29*, 603–625. [CrossRef]
74. Teng, J.T.; Grover, V.; Guttler, W. Information technology innovations: General diffusion patterns and its relationships to innovation characteristics. *IEEE Trans. Eng. Manag.* **2002**, *49*, 13–27. [CrossRef]
75. Hall, B.H.; Khan, B. *Adoption of New Technology*; Academic Press: Cambridge, MA, USA, 2003.
76. Senge, P.M.; Forrester, J.W. Tests for building confidence in system dynamics models. *Syst. Dyn. TIMS Stud. Manag. Sci.* **1980**, *14*, 209–228.
77. Van der Voet, E.; Van Oers, L.; Verboon, M.; Kuipers, K. Environmental implications of future demand scenarios for metals: Methodology and application to the case of seven major metals. *J. Ind. Ecol.* **2019**, *23*, 141–155. [CrossRef]
78. World Economic Forum (WEF). Aluminium for Climate: Exploring Pathways to Decarbonzie the Aluminium Industry. 2020. Available online: https://www3.weforum.org/docs/WEF_Aluminium_for_Climate_2020.pdf (accessed on 5 February 2024).
79. European Commission. The Future of European Competitiveness. 2024. Available online: https://commission.europa.eu/document/download/97e481fd-2dc3-412d-be4c-f152a8232961_en?filename=The%20future%20of%20European%20competitiveness%20_%20A%20competitiveness%20strategy%20for%20Europe.pdf (accessed on 21 September 2024).
80. Alcott, B. The sufficiency strategy: Would rich-world frugality lower environmental impact? *Ecol. Econ.* **2008**, *64*, 770–786. [CrossRef]
81. Statista (n.d.). Car-Sharing—Central & Western Europe. Available online: https://www.statista.com/outlook/mmo/shared-mobility/car-sharing/central-western-europe (accessed on 13 August 2024).
82. Statista (n.d.). Car-Sharing—Eastern Europe. Available online: https://www.statista.com/outlook/mmo/shared-mobility/car-sharing/eastern-europe (accessed on 13 August 2024).

83. Statista (n.d.). Car-Sharing—Southern Europe. Available online: https://www.statista.com/outlook/mmo/shared-mobility/car-sharing/southern-europe (accessed on 13 August 2024).
84. European Parliament. How to Reduce Packaging Waste in the EU (Infographics). 2024. Available online: https://www.europarl.europa.eu/topics/en/article/20231109STO09917/how-to-reduce-packaging-waste-in-the-eu-infographics (accessed on 13 August 2024).
85. Pragma Market Research. Global Reusable Packaging Market Size, Share, Growth Drivers, Trends, Opportunities, Revenue Analysis and Demand Forecast to 2032; Market Executive Summary. 2024. Available online: https://www.pragmamarketresearch.com/reports/121237/reusable-packaging-market-size?UTM=NikitaLin&trk=article-ssr-frontend-pulse_little-text-block (accessed on 13 August 2024).
86. Keuenhof, M. Personal Care in Reusable Aluminium Bottle. 2021. Available online: https://kidv.nl/translated-change-title-23 (accessed on 15 August 2024).
87. Bauer, A.M.; McIsaac, F.; Hallegatte, S. *How Delayed Learning about Climate Uncertainty Impacts Decarbonization Investment Strategies (No. 10743)*; The World Bank: Washington, DC, USA, 2024.
88. Zhang, A.; Alvi, M.F.; Gong, Y.; Wang, J.X. Overcoming barriers to supply chain decarbonization: Case studies of first movers. *Resour. Conserv. Recycl.* **2022**, *186*, 106536. [CrossRef]
89. Cao, T.; Sugiyama, M.; Ju, Y. Prospects of regional supply chain relocation for iron & steel industry decarbonization: A case study of Japan and Australia. *Resour. Conserv. Recycl.* **2024**, *209*, 107804.
90. Yu, M.; Liu, K.; Li, W. Decarbonizing innovation investment strategy in competing supply chains considering technology spillovers and environmental regulation. *Expert Syst. Appl.* **2024**, *238*, 122106. [CrossRef]
91. EEA. Accelerating the Circular Economy in Europe State and Outlook 2024. EEA Report 13/2023. 2023. Available online: https://www.eea.europa.eu/en/newsroom/news/now-is-the-time-to#:~:text=Decisive%20action%20is%20essential%20to,assessment%20on%20the%20circular%20economy, (accessed on 3 October 2024).
92. EEB. A Policy Approach to Reduce Resource Use and Accelerate the Transition to a Circular Economy, Final Report. 2022. Available online: https://eeb.org/wp-content/uploads/2022/11/Circular-Taxation-study-EEB-Final-Report.pdf (accessed on 3 October 2024).