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Policy mixes and policy feedback: Implications for green industrial growth in the Swedish biofuels industry

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ABSTRACT

Policymakers have increasingly voiced an ambition to combine the transition to a climate-neutral society with a "green" domestic industrial agenda. In recent years, innovation systems scholars have advanced the understanding of the evolution of industries around renewable energy technologies as well as the role of policy feedback (and indeed politics) surrounding the development of domestic green industrial development policies. To take a step towards combining these literature streams, the purpose of this paper is to investigate the role of policy mixes and policy feedback in the emergence of domestic green industries. This is achieved in the empirical case of biofuels in Sweden, and the findings show that policy feedback dynamics created difficulties in aligning the national policy mix with the technology and industrial developments in the country. The resulting political uncertainty predominantly hampered the scaling up of domestic production capacity, while R&D and import of biofuels instead could grow strong. Based on this empirical case, a process model is developed to explain the role of policy feedback in the development of domestic industries, thus demonstrating how the growth of domestic industries is driven by the interplay of policy effects and various feedback processes. The findings suggest that future research into the role of policies in "green" domestic industry growth should devote more attention to the dynamics driving the co-evolution of policy, technology and industry structures.

1. Introduction

In response to the 2015 Climate Paris Agreement to limit global warming to 1.5 °C, countries increasingly set goals to attain net zero emissions in the coming decades. Achieving such goals requires a fundamental transformation of the energy sector, based largely on an accelerated implementation of renewable or low-carbon technologies [1]. In this context, there is growing political interest in combining the scale-up and utilisation of such technologies with domestic industrialisation and growth [2]. The German hydrogen industrial strategy [3] and the Swedish ambition to promote domestic biofuel production [4] are two of many such examples.

The emergence of domestic industries associated with new technologies has attracted considerable interest in the innovation systems literature in recent decades (for a recent review, see Bergek [5]). This research suggests that industrial development is supported by the emergence of innovation systems, in which actors, networks, and institutions interact to help develop and adopt new technologies [6]. This literature has reported wide variation in the abilities of different countries to localise domestic industries (e.g., Quitzow [7] on solar PV in Germany and China), and has argued that the structure and characteristics of domestic innovation systems can help explain such differences [8]. In recent years, the debate has continued about the opportunities and challenges for national policymakers to influence the structural development of domestic green industries. Building upon ideas on policy design in the literature on public policies [9–11], innovation system scholars have reported that the design of domestic innovation policies has played a vital role in bringing about different value chain sectors [12] and industrial structures [13]. For example, Hedeler et al. [14] found that differences in the design and sequencing of innovation policy mixes have led to varying domestic biofuel industry structures in Finland and Sweden.

However, there has been little analysis on the dynamics underlying the growth of domestic technology and industrial structures, with related policy-mix adjustments over time. While recent studies emphasise the importance of policy design and timing for different industry structures to emerge, they provide limited insight into the opportunities and challenges for policymakers to implement changes in policy mixes

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(e.g., due to the presence of path dependencies and politics). This is particularly noteworthy given the frequent political constraints surrounding the development of domestic green industrial development policies [15]. Hence, there is much to gain from incorporating a dynamic policy perspective into innovation system studies to better understand the relationship between policy mix design and the emergence of domestic green industries.

The theme of policy development in the context of technological innovation and associated industry growth has received considerable attention in the innovation systems literature. Past innovation system scholars have emphasised mutual influences between institutions and industrial actors [16], as well as path dependencies and increasing returns to adoption in both policies and technological change processes [17]. For example, Jacobsson and Lauber [18] found that the speedy diffusion of wind turbines and solar PV in Germany was facilitated by strong support from various innovation system actors. The notion that various policies, once implemented, influence subsequent rounds of policymaking is a core interest of policy feedback scholars. Their work typically focuses on policy as the main variable of interest, and investigate how and why policies change over time (e.g. [19,20]). More recently, the policy feedback approach has also informed work on sustainability transitions [21]. These studies have shown that policy feedback affects the long-term development of policy mixes and has implications for the speed and direction of sociotechnical change [22]. A few studies have investigated the role of different actor networks in relation to different segments of policy feedback. For example, Gomel and Rogge [15] found that in Argentina, power imbalances between different actor networks interested in the domestic production of renewable energy and energy imports led to policy mix adjustments in favour of the more powerful advocacy coalition. Although insightful, these studies provide limited knowledge about the complexities and the interconnectedness underpinning industrial development. Incorporating the policy feedback perspective into the innovation systems approach should therefore help generate novel insights.

The general purpose of this paper is to analyse the role of policy mix and policy feedback in the emergence of domestic green industries. Specifically, the paper seeks to answer the following research question (one question in two interrelated parts):

RQ1a. How does the development of policy mixes influence the emergence of technologies and industrial structures?

RQ1b. How have the actors representing these technologies and industrial structures in turn influenced policy mix development?

To this end, this paper departs from the innovation systems literature and draws on insights from policy feedback studies to conceptualise the development of policies over time. Empirically, the paper is based on the case of biofuels in Sweden, and illustrates how the development of the country's biofuel policy mix has affected which technologies and industrial structures that emerge and expand over time. Based on the empirical analysis a process model is derived. This model attempts to explain how causal influences may affect the evolution of national policy mixes and subsequent domestic technology and industrial structures. It contributes to past innovation system studies by explicitly considering the role of policy development for the evolutionary dynamics in industrialisation processes. In this way, it is argued, new knowledge about the evolution of innovation systems to explain domestic industry growth can be provided. Moreover, the paper highlights important lessons for policy by building on both the policy feedback literature and related discussions on harnessing policy feedback for policy design [23–25].

The paper proceeds as follows. In Section 2, the existing literature on innovation systems and policy feedback is reviewed. The paper then builds an analytical framework in Section 3. Section 4 lays out the reasons for case selection, provides additional background on biofuel development in Sweden, and discusses the methods and the data used. In Section 5, the paper presents the findings of the case study analysis, focusing on the mechanisms that have propelled the development of the Swedish policy mix and the country's biofuel technology and industrial structures. Section 6 discusses the wider implications of the findings, including some lessons for policymakers. In concluding the paper, a few avenues for future research are identified.

2. Theoretical background

2.1. Domestic perspective on institutions, technological change, and industrial dynamics

Innovation systems scholars seek to understand and explain the abilities of countries to exploit technological innovation for domestic industrialisation processes [6]. They argue that innovation systems are important in supporting and directing innovation processes, including policy and regulatory frameworks (for a recent review, see Bergek [5]). An innovation system consists of "a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilisation of technology," (Carlsson and Stankiewicz [26], p. 94).

To uncover the dynamics, innovation system scholars draw inspiration from cyclical models of technology and industry development [27]. These models suggest that industries emerge through relatively ordered processes, displaying similar evolutionary patterns of variety creation and selection [28–30]. Innovation system scholars highlight the importance of system development and functioning to support technology-driven industrialisation [17]. They typically distinguish between two phases in this process: formation and growth [31]. The formative phase is characterised by the creation of technological variety and the entry of firms from different sectors [31]. In the growth phase, the focus moves to the diffusion and expansion of the new technologies, achieved through cost reductions and by exploiting economies of scale [31].

The variation and selection model has been criticised for its marked simplification of the interaction dynamics between technologies and products [32,33]. Sandén and Hillman [32] argue that multiple modes of interaction could emerge between technological variants (ranging from competition to collaboration) and suggest that technologies may be defined as combinations of technology, industrial structures and institutions (see also Nelson [16]). Sandén and Hillman [32] proposes that each technology may be unfolded to different hierarchical levels. This work has inspired studies investigating the innovation dynamics at various aggregation levels (e.g. [34,35]), showing that different constellations of technology, firms and industrial structures have emerged within renewable energy technologies, highlighting their spatial distribution across one or more countries [35].

Other work following this line of argumentation focuses on the formation of domestic technology, firms, and industrial structures in the context of global industry dynamics. One central conclusion of this line of research is that complex domestic industrial structures emerge, with variable integration of actors and firms integrated into global value chains. Related studies addressing the impact of policy mixes on the emergence of domestic industrial structures have emphasised the role of policy design and implementation. Building upon the work on policy mixes in the public policy literature [9], these studies show that different firms [13], technologies and industrial structures [14] need different forms of policy support in terms of combination and sequencing. Imports of renewable energies often result from the implementation of demand-pull policies, while stimulating technological innovation and domestic commercialisation processes could often require more ambitious and directed political support and adjustment [14].

Table 1
Overview of the policy feedback concept, building on Edmondson et al. [21]. The concept differentiates between policy effects and feedback mechanisms, which both can be both positive or negative.

Segment	Mechanism	Description
Policy effects	Resource effect	Distributing resources (e.g., RD&D funds)
	Interpretative effect	Legitimation and guidance of search (e.g., visions or roadmaps)
	Institutional effect	Reconfiguration of institutional structure (e.g., establish new state capacities to design, evaluate and enforce compliance with policies)
Policy Feedback	Socio-political feedback	Interpretation of the effectiveness of the policy mix (e.g., perceiving target levels as too low)
	Fiscal feedback	Cognition of financial burden of policy mix (e.g., perceiving costs as too high)
	Administrative feedback	Perception of responsible public bodies (e.g., perceived lack of knowledge)

While the literature on innovation systems has generated valuable insights into industrial development at the national levels and the role of policy mixes therein, these studies have devoted less attention to mutual causal influences between institutions and policy mixes on the one hand and the formation of technology and industrial structures in innovation systems on the other. Additional work in the innovation systems literature has stressed that both institutions and technologies benefit from increasing returns to adoption and that these may be mutually reinforcing [36]. This, in turn, will affect and limit the development and adoption of alternative "green" technologies [37–39]. Yet, while recent studies have revealed the salience of politics and path dependency in the evolution of domestic industrial growth policies [15], the detailed mechanisms connecting the evolution of policies and industrial activities remain elusive. Hence, by adding a policy feedback perspective, more can be learned about the causal mechanisms driving the co-evolution of policy mixes, technologies, and industrial structures.

2.2. Policy feedback

The literature on policy feedback has sought to explain the mechanisms and dynamics through which earlier policies affect later ones.[1] The main argument is thus that the implemented policies influence politics and subsequent rounds of policymaking [19,20]. In describing such path dependencies, this literature lists so-called resource and interpretative effects as the main types of feedback [20]. Resource effects describe actors' changing capacities through, for instance, the provision of funding [20]. Interpretative effects influence the interests and cognitive processes of actors, for example, by learning from the impacts of past policies [20]. In more recent years, scholarly attention has turned towards studying the entire feedback loop, from the implementation of policies, the emergence of policy feedback to subsequent policy mix changes ([40]).

Research into the sustainability transitions context has started to build on the policy feedback research, to understand how feedback and stability can build momentum for transition processes [24,41]. The transitions approach explains sociotechnical change as an alignment process [42], and emphasises that sociotechnical change occurs as new technologies gain momentum from niche processes and replace the existing regime [43]. Studies of policy feedback in the sustainability transitions context therefore seek to investigate the processes and mechanisms that drive the co-evolutionary process between policy mixes and sociotechnical change [21,22]. To combine both theoretical approaches, three adjustments have been suggested.

Firstly, the policy feedback concept has been expanded to also address policy mixes. A policy mix is defined as combination of a policy strategy (i.e., policy objectives and plans for how to achieve these objectives) and an instrument mix, typically entailing demand-pull, technology-push and systemic instruments [44]. Secondly, to conceptualise the elements of sociotechnical change in relation to policy feedback loops, Edmondson et al. [21] suggest distinguishing between policy effects and feedback mechanisms, as summarised in Table 1. Policy effects refer to the impact of a policy mix on sociotechnical change, while subsequently occurring feedback processes describe the political behaviour of actors [21]. Thirdly, Edmondson et al. [21] draw on pre-existing conceptualisations of sociotechnical change [43] and introduce the influence of exogenous influences [21].

For socio-technical systems, the mutual influences between policy mixes and sociotechnical change may lead to either positive feedback (which lead to progress in terms of sociotechnical change and future policy mixes), or the emergence of negative feedback dynamics, with subsequent failed transitions and the abandonment of the necessary policy mixes [21,22].

The above literature provides valuable insights into the influence of past policies on future policy development. Yet, these studies put relatively limited emphasis on the micro-level dynamics within innovation systems, such as the formation of networks along value chains and technological diversity. This is in spite of the fact that policy feedback studies have stressed the differences between actors and actor networks in generating policy feedback [45]. For example, recent policy feedback work within US biofuel development revealed that, over time, policy did produce both positive and negative feedback dynamics for different actors [46]. Still, this and other related studies focus on the nature of the policy feedback rather than on their interplay with technological change from a systems perspective.

Finally, it is also worth emphasising that recent studies have proposed that multiple technology-policy paths emerge in innovation processes, suggesting that the interaction dynamics between these paths impacts the evolution of technologies and policy [25,47]. However, the configuration of such paths and the interplay of multiple paths have been less detailed and, thus far, lacking empirical application.

3. Analytical framework

The research reviewed in Section 2 provides important insights into the relationships between policy, technological innovation, and industrial structures. While the innovation systems literature posits a critical role for evolutionary dynamics between technologies and industrial structures, the research on policy feedback in sustainability transitions highlights the influence of past policies on policymaking and policy mix adjustments. In view of the above, one may suppose that the development of policy mixes is associated with considerable challenges in the presence of diverse technologies and industrial structures.

Fig. 1 illustrates the analytical framework of the paper. In brief, this framework consists of a policy mix and a variety of technologies and industrial structures and their interaction.

The innovation systems approach offers an effective way of delineating a country's industrialisation processes. This delineation is useful also for the analytical framework of this paper. As illustrated in Fig. 1, a domestic innovation system is embedded in a global innovation system, and consists of institutions, technologies, and industrial structures.

[1] These studies typically choose one specific policy instrument as the main focus of analysis (see Ref. [70] for a recent review).

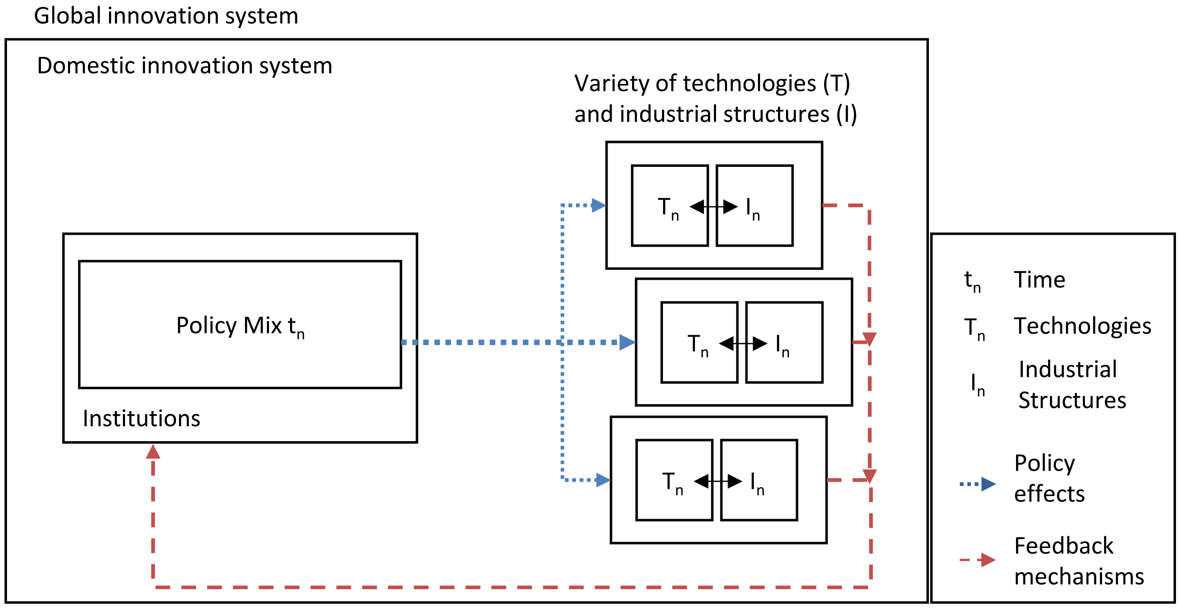

Fig. 1. Analytical framework.

Building on the work of Sandén and Hillman [32], this paper further disaggregates the technological field into technological variants and related products. The innovation system, it is argued, consists of policy mixes embedded in a certain institutional context, plus the actors and networks that form the firms and the industrial structures. Furthermore, it is assumed that multiple paths of technologies, firms and industrial structures can emerge in parallel to institutions and the policy mix. This is particularly important given the focus on national settings, and implies that parts of the industrial structure along value chains may be located globally.

Following the innovation systems approach, this paper assumes an evolutionary-based explanation of innovation and industrial development. This implies that selection processes between actors, technologies and products shape the dynamics within innovation systems that lead to the formation of the domestic industry structure over time. To further conceptualise the link between the policy mix on the on hand and technologies and industrial structures on the other, ideas from the research on policy feedback in sustainability transitions [15,21,45,48] are also incorporated. As illustrated in Fig. 1, institutions and policy mixes are linked to the technology and industrial structure through both policy effects and feedback processes. In a domestic industrialisation context, one may suppose that a wide range of different innovation system actors engage in various industrial activities, from the development of technological alternatives to the production and imports of renewable energies. The emergence of such technologies and industrial structures is likely induced by various policy effects and feedback mechanisms. Depending on the created policy feedback dynamics, it can be assumed that the policy mix may enable the growth of some technologies and industrial structures, whereas it may represent a constraint to others.

The empirical analysis will primarily reveal the interplay of these policy feedback with the wider innovation system dynamics and the resulting formation of domestic green industries.

4. Methodology

To investigate how policy development affects the emergence of technologies and industrial structures, leading to the growth of domestic green industries, this paper draws on a processual case study approach. The use of single case studies is a well-established approach to uncover underlying mechanisms [49] and has been widely applied in the innovation systems literature (for a recent review, see Köhler et al. [50]). The following two sections explain the rationale for case selection, and describe the data and methods used in the analysis.

4.1. Case description

This paper draws on the empirical case of biofuel development in Sweden over the period 2003–2020. This case has been selected for several reasons. Firstly, biofuels are considered highly relevant for decarbonising the energy system and could turn into an important source of renewable energy for the transport sector in coming decades [51].[2] Secondly, it has been shown repeatedly that, to date, the development and the diffusion of biofuel technologies have largely been driven by public policies [52]. Thirdly, it has suggested that biofuel value chains may to different extents be organised locally or distributed across different countries [53].

The political support for biofuels in Sweden dates back to the 1970s, as a result of the global oil crises and oil import dependencies [54]. With the introduction of carbon taxes in 1991 and since 2003 under the framework of the EU biofuel policy, it has once again become an important topic. Consequently, it is argued that the long history of policy support in Sweden is suitable for studying policy dynamics. Moreover, diverse biofuel technologies, firms and industrial structures have emerged gradually in Sweden. Table 2 shows the main biofuel technologies with the products and complexity of the technology architectures varying substantially. There are some drop-in products, such as HVO or low-blended ethanol, while other products require adaptation of the fuel infrastructure and vehicle fleet. In 2019, Sweden had a 20%

[2] Generally, biofuels can be produced using different combinations of feedstocks and conversion processes that are commonly distinguished as first generation (1G, food crops) and second generation (2G, non-edible feedstock). The conversion processes used for the different generations of feedstock differ in terms of complexity and level of development (for a recent review, see Callegari et al. [77]). The resulting biofuel pathways may in turn differ a lot in terms of carbon mitigation potential, depending on the chosen feedstock and conversion process.

Table 2
Overview of biofuel technologies in Sweden, following [32] and differentiated by chemical composition of fuel [56].

Type of fuel	Raw material	Conversion process	Distribution infrastructure[a]	Vehicle types[a]
Ethanol	Sugar-rich feedstock (1G and 2G)	Bioprocessing	Drop-in (low-admixture)	Drop-in
			Adapted filling stations	Adapted cars
Biogas (large-scale)	Forest residue/wood chips	Gasification	Adapted filling stations	Adapted cars
Hydrotreated vegetable oils	Several feedstocks, such as tall oil, animal fats and waste oils, palm oil	Hydrotreatment	Drop-in (blending levels)	Drop-in
Biodiesel (Fatty Acid Methyl Ester (FAME)/ Raps Methyl Ester (RME))	Oil-bearing plants	Bioprocessing	Drop-in (low admixture)	Drop-in
			Adapted filling stations	Adapted cars
Syngas fuels	Sawdust/forest residues	Thermochemical conversion	Drop-in	Drop-in
	Forest residue/wood chips	Thermochemical conversion	Adapted filling stations	Adapted cars

[a] "Drop-in" describes fuels that can be used in the traditional distribution infrastructure without any adjustment.

share of biofuels (17 TWh) in the transport sector, ranking the highest in Europe [55]. A detailed description of the technologies and associated firms and industrial structures is provided in Table A4.

Taken collectively, the case of biofuels in Sweden may arguably be considered a typical (representative) country with dual policy ambitions [57], given the high degree of political commitment to biofuels as a means of achieving sustainability transitions, plus the diversity of technologies and the difficulties creating domestic industrial structures. This allows the focus to be on the causal mechanisms that drove the development of the Swedish case. Furthermore, it allows the derivation of largely representative conclusions on the dynamics and mechanisms underpinning the development of policy mixes and green industrial structures [57].

For the analysis, the period from 2003 to 2020 was chosen. This was because in 2003, the European Union mandated all Member States to implement domestic biofuel policies (Directive 2003/30/EC). This allows the development of biofuel policies in Sweden to be studied, whilst also taking international developments into account. For the purposes of the present work, the system boundaries were set to biofuels for road transport. This paper draws on the definition of value chains proposed by Stephan et al. [58], thus distinguishing between sectors involved in the production (capital goods industry) of biofuel technologies and the user sectors (in terms of raw materials, biofuel production, distribution and end-use) (see also Gregg et al. [59]). The research community has been included as a supporting sector [58].

4.2. Research design

To investigate how feedback in the Swedish biofuel policy development have affected the emergence of technologies and industrial structures, which, cumulated over time, have led to domestic biofuel industry growth, this paper uses a qualitative research design. This section first describes the data types, sources, and collection and then moves on to outline the strategies pursued to analyse and synthesise the data.

Table 3 provides an overview of the data types, sources, and collection used in this paper, as well as the link to the analytical framework. Specifically, to map and analyse the Swedish biofuel innovation system with a particular focus on emerging biofuel technologies and industrial structures, this paper draws on two main data types. Firstly, archival data were collected through an internet search, comprising different sources, such as policy documents, annual company reports, and scientific articles (see Table A1 in the appendix for a detailed overview). Scientific articles were retrieved from the database Scopus (see Table A5 for a list of keywords). Secondly, interview data were collected through semi-structured interviews with representatives of government authorities, industry, and research/consulting, as outlined in Table A2. These 60–90-min interviews were conducted in person or over the phone and were all recorded and transcribed. Besides the emergence of the Swedish biofuel innovation system, data were collected to map the policy effects and feedback driving the development of the Swedish biofuel policy mix. To better understand policy effects and feedback, newspaper articles were retrieved, covering the period 2003–2021. For this purpose, the Swedish newspaper *Dagens*

Table 3
Overview of data types, sources, and collection and link to the analytical framework.

Link to the analytical framework	Data types	Sources	Collection
Mapping of technologies, industrial structures, and innovation system dynamics	Archival data	Policy documents, annual company reports, scientific articles	Internet search
	Interview data	Interviews with representatives from Swedish biofuel policy, industry, and research	Semi-structured interviews, conducted in person or over the phone
Mapping of policy effects and feedback	Newspaper articles	Database (Mediearkivet)	Retrieval from database
	R&D projects	Database (Swedish Energy Agency)	Retrieval from database

Nyheter was selected due to its national coverage and the availability of full-text articles over the period being studied. Using the Swedish term for "biofuels" in the Mediearkivet database yielded a total of 443 articles in *Dagens Nyheter*. In the analysis editorials were excluded. The focus was set on full length articles that comment on how, for instance, industry representatives, politicians, and civil servants argue about the future of biofuel policy in the country. Additionally, the data were supplemented by information on biofuel R&D projects funded by the Swedish Energy Agency between 2003 and 2021. In total, 1091 projects were retrieved from the publicly accessible database of the Swedish Energy Agency.

The subsequent data analysis and synthesis were conducted in three steps. Firstly, to analyse the emergence of the Swedish biofuel innovation system and the role of the policy mix therein, with a particular focus on emerging technologies and associated industrial structures, this paper followed the bottom-up approach outlined in Ossenbrink et al. [60]. Drawing on archival data, the sectoral developments were mapped, plus the actor networks involved in the value chains, as defined in Table 2. Then, the analysis focused specifically on the influence of policy instruments and strategies on the development of industrial value chains. Archival data, such as policy documents, written notes, and laws (see Table A1), were used to add detailed knowledge about the underlying policy instruments and strategies. The visual mapping strategy outlined by Langley [61] was followed to produce a visual timeline, and a thick narrative (of roughly 30 pages) was constructed to describe the development of the Swedish case.

Secondly, to better understand the development of the Swedish biofuel policy mix through the lens of policy feedback theory, the policy mix development was reconstructed, with a particular focus on the created policy effects and feedback (as outlined in section 3). Using the NVivo software, the newspaper articles were coded according to the policy effects and feedback mechanisms outlined in Table 1. To deepen the understanding of the resource and interpretative effects on the different technologies and value chains, the data were supplemented by an analysis of R&D expenditure and distribution. The projects were coded according to technologies and value chain segments, and the identified policy feedback segments.

Thirdly, to synthesise the findings generated in the two preceding steps, the feedback mechanisms driving the biofuel policy mix development were incorporated into the emergence of the Swedish biofuel innovation system. To this end, the temporal bracketing strategy was followed as outlined by Langley [61] to define five distinct phases based on the main development of the Swedish policy mix. In the analysis, this paper builds on Edmondson et al. [21], and employs the following abbreviations to highlight the occurrence of the analytical constructs and mechanisms in the empirical material: policy mix change "PMC",

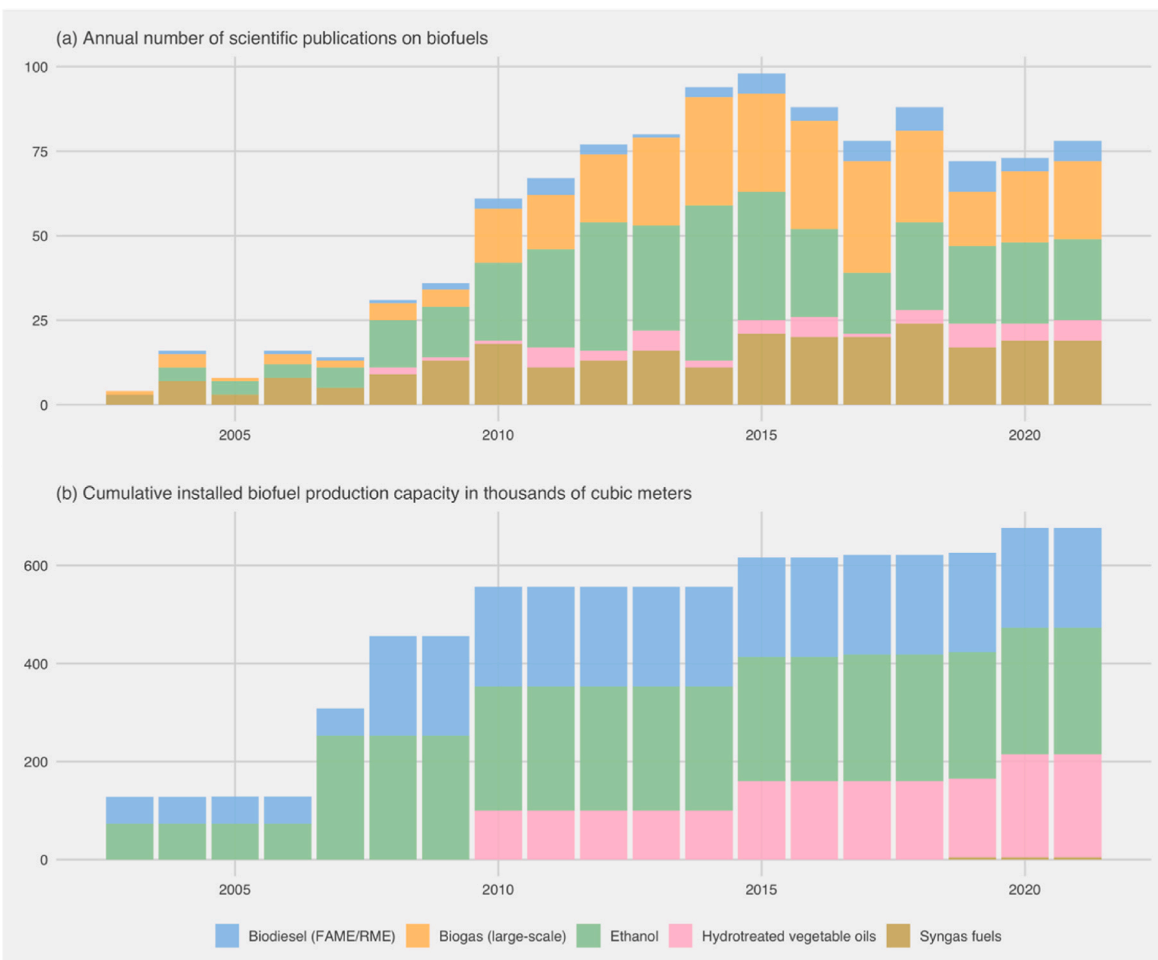

Fig. 2. Development of industrial activities related to (a) knowledge development measured in annual number of scientific publications and (b) the cumulative installed biofuel production capacity (own illustration, data source: Scopus, see Table A5 for a list of keywords (a), Bioenergy [63] (b)).

exogenous conditions "ExC", resource "RE", interpretative "IntE", and institutional "InstE" effects; socio-political "SPF", fiscal "FF" and administrative "AF" feedback. To further theorise the empirical findings, these are synthesised in a process model. This entailed process tracing, a qualitative analysis strategy for uncovering sequences of mechanisms and dynamics [62].

5. Case study analysis

5.1. Historical development of biofuels in Sweden

This section explains the development of the Swedish biofuels industry over the period 2003–2020. It focuses on the interaction between the biofuel policy mix and the technology and industrial structure over five distinct phases.

To support the analysis, Fig. 2(a–b) and Fig. 3 summarise the development over time of the industrial activities related to knowledge development, domestic production and end-use. Fig. 2 illustrates a) the number of Swedish scientific publications on biofuels; b) the domestic installed production capacity; and Fig. 3 shows the share of biofuels used in road transports out of total fuel use. These figures are quite revealing in several ways. Firstly, the period 2003–2020 involves a general increase in the interest in biofuels. Secondly, although domestic production capacity increased consistently over the period, the share of domestically produced fuels in total Swedish biofuel use has remained low (most are imported). Thirdly, the dip in the biofuel shares after 2017 can be explained by the introduction of the reduction obligation in 2018. Fuel distributors have tuned their systems to meet quota requirements.

5.1.1. Phase 1: 2003–2005

The political interest in biofuels emerged in Sweden during the 1970s [PMC], much due to the global oil crises [ExC]. With the aim of reducing Sweden's dependency on crude oil imports, public RD&D expenditure stimulated research activity to develop technological approaches to converting Sweden's abundant forest resources into biofuels [54,65]. As the pressure from the oil crises faded, the political interest in biofuels was revitalised by growing environmental and climate concerns [ExC]. During this phase, ethanol was considered the most promising fuel type [+SPF] (Interview 11). The result was public RD&D expenditure on two largely independent, small-scale experiments involving the conversion of wheat and woody feedstock [+RE, IE]. Carbon taxation exemptions for biofuels produced in pilot projects enabled the first wheat ethanol to be distributed in Sweden in 2001 [+RE]. However, these industrial activities were small in scale.

In 2003, the European Commission (EC) introduced the Biofuels Directive (2003/30/EC) to promote the use of biofuels by Member States [ExC]. In Sweden, this was received with great enthusiasm among existing actor networks and small farmers interested in small-scale production [+IntE] (Interview 11). The Swedish government decided to follow what it considered a strategy reliant on reaching existing

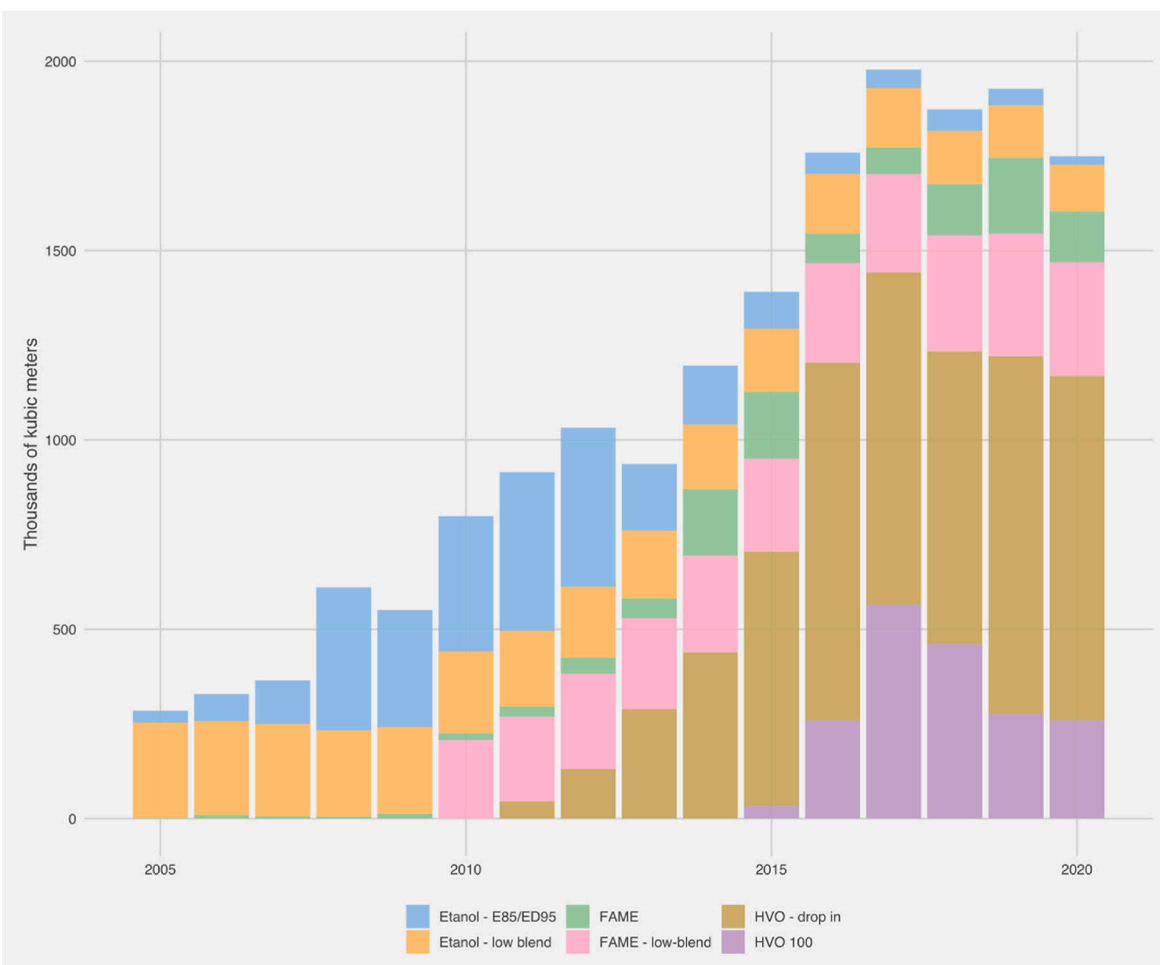

Fig. 3. Development of the end-use of biofuels in Swedish road transport (own illustration, data source: Drivkraft Sverige [64]).

(short-term) targets cost-effectively through biofuel imports and exempting biofuels from carbon taxation.[3] Alongside an increased use of biofuels, the strategy included the goal of stimulating the development of advanced 2G technologies, converting woody biomass to biofuels, while stimulating domestic production and industrial development (SOU 2004:133). This strategy was backed by increasing, long-term public RD&D funding [PMC].

Through the resource effects from the changed taxation system, importing and distribution of biofuels became economically viable for importers and oil companies [+RE]. In practice, however, only ethanol was available internationally in large volumes and at a low cost [ExC]. This, in turn, led to substantial growth in importer structures and ethanol uptake (Interview 4, Fig. 3).

The above policy mix also helped mobilize existing research networks [+IntE]. Public RD&D expenditures enabled the existing cellulosic-focused network to construct a pilot plant [+RE]. Additional resources were allocated to an existing actor network working on the gasification of black liquor.[4] This development, comprising the technology developer Chemrec and its academic partners, was supported by the domestic car manufacturer Volvo (Interview 1). Due to the resource effects [+RE] produced, plus the interpretative effects of strong political support [+IntE], two large-scale pilot projects materialised.

However, the imported ethanol threatened the profitability of domestic wheat ethanol, causing the Swedish agricultural cooperative Lantmännen to oppose the tax exemptions for imported ethanol [-SPF]. In 2004, additional problems emerged as the low-admixture ethanol market was saturated, while a high-admixture niche market would have required large-scale expansion of an adapted fuel infrastructure and flexi-fuel cars (Interview 4). Since the oil companies hesitated to invest in the large-scale installation of high-admixture fuel infrastructure, the importers mobilised and advocated policies that could address the lack of filling stations [-SPF]. This was further reinforced by a small number of very optimistic flexi-fuel car drivers [-SPF]. The government issued a policy evaluation report, which concluded that poor market formation was limiting the uptake of biofuels (SOU 2004:133) [-SPF].

The monitoring report also revealed problems with the taxation of imported ethanol (Interview 3). It concluded that the tax exemption's design had resulted in overcompensation (SOU 2004:133) [PMC]. In other words, it risked violating existing EU state aid regulations [ExC] and thus required further adjustment. Moreover, another monitoring report revealed higher-than-anticipated public tax losses due to the carbon tax exemption [PMC] (Swedish Environmental Protection Agency, 2004). This led to a first debate on the fiscal effects of the Swedish taxation strategy with respect to biofuels [-FF].

5.1.2. Phase 2: 2006–2009

In 2006, to comply with EU regulations, the Swedish government addressed the carbon taxation problems for ethanol and the threatening market saturation by introducing higher rates of duty on imported ethanol supplied through the low-admixture market. Ethanol for higher percentage blends could still be imported at lower rates (Table A3 in Appendix).[5] To further foster growth in the high-admixture market, the government implemented economic incentives for public and private actors to invest in flexi-fuel cars and introduced a so-called "pump law" (2005:1248), stipulating that fuel suppliers had to install biofuel dispensers.

The resource effects [+RE] brought about by the above policy measures induced a steep increase in the use of high-admixture ethanol (Fig. 2a). It also signalled strong political commitment [+IntE] which, in turn, triggered further investment in the growth of importer structures. These changes, combined with increasing crude oil prices, provided a market for domestic wheat ethanol in the low-admixture market segment [+RE]. The domestic producer Lantmännen expanded its production capacity in 2007 (Fig. 2). The prospect of a domestic industry for agricultural biofuels also revived interest from actors interested in RME production [+IE], motivating them to advocate for policy support [-SPF]. Their position got an added boost from steadily rising crude oil prices, prompting the government to declare that becoming independent of fossil fuel was a top priority [ExC]. Thus, greater emphasis was put on reducing the fossil fuel dependence of the transport sector. This resulted in increased blending levels and regulations permitting the conversion of conventional fuel car engines to flexi-fuel cars [PMC]. The resource effects [+RE] generated by these measures induced further growth in ethanol use (Fig. 3).

The changes also created a market, and increased legitimacy for 1G biodiesel (FAME) [+RE, +IntE], which triggered a growth in importer structures and new plans to produce 1G biodiesel (FAME) [STC]. However, the momentum for 1G biofuels did not last long. Rising feedstock prices, a sudden drop in crude oil prices and the financial crisis [ExC] in 2008, diminished the profitability of the planned projects. Ultimately, only two commercial FAME plants materialised [+STC] (Fig. 3, Table A4).

While the legitimation of biofuels was challenged internationally [ExC], Swedish industry and policy remained positive. The narrative which evolved stated that a more differentiated view on biofuels was needed, suggesting that sustainability problems in biofuel production mostly occur abroad [+SPF]. Thus, the industrial activities remained largely unaffected [STC], while lending additional momentum to 2G biofuels [+IntE]. In 2006, the newly elected Swedish government [PSC] provided the vision to move towards domestic, wood-based biofuel production [+IntE], and additional experimentation with different technologies was initiated [STC]. The existing actor networks (working with woody ethanol and black-liquor gasification) verified their technologies (DME, methanol) on a pilot scale, using DME in their first test runs with the Swedish vehicle manufacturer Volvo (Interview 7). New actor networks also formed around large-scale gasification (Gobigas) and the hydrotreating of tall oil (Sunpine).

Meanwhile, the global anti-biofuels discourse continued to gain strength [ExC]. Sustained by a series of scientific reports on the harmful effects of biofuels [-SPF], political support for biofuels within the EU continued to weaken [ExC].[6] In Sweden, a debate emerged on the disadvantages of ethanol [PMC], weakening the interest in 1G ethanol [-STC]. The global financial crises [ExC] also hit the ethanol fuel importers quite hard [-RE]. Talloil went bankrupt and SEKAB got into extreme financial difficulties but managed to survive. However, 2G biofuels still had momentum. Significant plans for scaling up the 2G technological developments were made [+SPF].

Volvo was generally supportive of the biofuel developments [+SPF] but still moved to advocate for more political guidance and the long-term prospects of fuel choices[7] [-SPF] (Interview 8). This call for political directionality coincided with feedback emerging from a political review mechanism of Swedish climate policy (SOU 2008:24) [ExC]. The suggestions developed in this investigation included increasing the EU 2020 transport target, working towards abandonment of EU customs

[3] Sweden introduced a general carbon dioxide tax in 1991 (Law 1990:582).

[4] This network emerged in the early 1990s. However, as interest in gasification declined, the network survived in the heat and power field [54].

[5] Three different customs tariffs for ethanol import were in place, with different taxation rates: 6.5% of the goods' value to import E85 and ED95 as chemical products (KN-nr 3824 90 99); EUR 19.20 per 100 L to import undenatured ethanol for low-admixture ethanol (KN-nr 2207 10 00; and EUR 10.60 per 100 L to import denatured ethanol (KN-nr 2207 20 00) for the production of E85 [73].

[6] For instance, the EU Commission decided to withdraw the planned 10% biofuel steering goal for 2020, opting instead for renewable energy targets, as stipulated in the Renewable Energy Directive (2009/28/EC).

[7] See Table 2 for an overview of the required vehicle and infrastructure adaptations of the different fuel types.

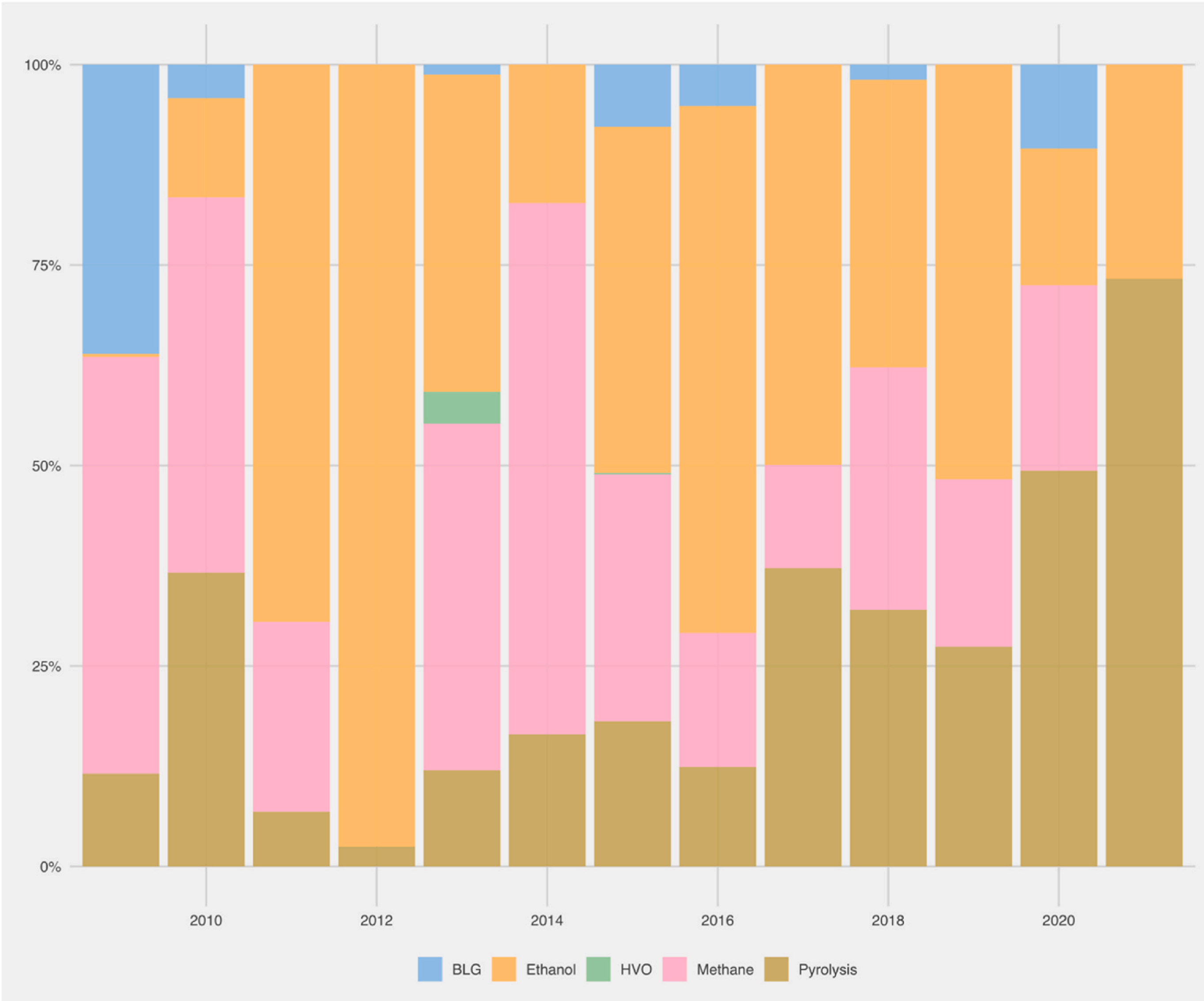

Fig. 4. Annual distribution of R&D funding by the Swedish Energy Agency according to the main biofuel technologies (data source: Swedish Energy Agency [66]).

tariffs, a certification system for sustainable biofuels, a unified definition of the environmental car, development of 2G biofuels and investments in vehicle research, plus investigation of policy instruments to stimulate biofuels. Meanwhile, despite these political uncertainties, Volvo, pressured by stricter EU regulation on exhaust emissions, announced that it would be backing gas-powered cars (Interview 8).

5.1.3. Phase 3: 2009–2013

In 2009, the Swedish government made several changes to the policy mix, thereby increasing biofuel use target levels and creating further support for domestic production [PMC]. With additional pressure from planned changes to EU state aid rules, aggravating tax exemptions for renewable energy support (due to such things as overcompensation rules [ExC]) and the subsequent creation of a negative national fiscal feedback [-FF], work began to replace the tax exemption system with a blending quota for fuel distributors by the end of 2013 (Interview 3) [PMC].

An additional SEK 875 million [+RE] was allocated to accelerate the development of 2G biofuel technologies. This signalled strong political commitment, despite the anti-biofuel movement in the EU [IntE]. This led to the funding of BLG demonstrations and large-scale biomethane technologies [STC]. The Swedish Energy Agency also funded [+RE] a woody ethanol demonstration project (Sekab) [STC]. These demonstration projects quickly attracted international interest [+SPF], resulting in raised expectations among policymakers (Interview 3), and triggered the launch of new government subsidy programmes [RE, IntE] (Interview 1). Influenced by the global feedstock scarcity discourse [ExC], new research emerged into processes for converting woody raw materials, especially lignin (Interview 1).

However, uncertainties emerged concerning the high-admixture market [-IntE]. While financial support for the installation of filling stations was prolonged [PMC + RE], the Swedish government removed the clean vehicles premium [-PMC]. There was a sharp decline in vehicle sales [-IntE] and an abrupt reduction in the attractiveness of ethanol [STC] due to falling crude oil prices linked to the global financial crisis [ExC]. Flexi-fuel car drivers subsequently began choosing petrol due to the lower prices [-STC]. In 2009, therefore, the positive trend in the high-admixture market changed for the first time (Fig. 3). This mobilised the fuel distributors to advocate for policy support [-SPF]. This policy feedback resulted in lowered biofuel tax levels [PMC], aimed at stabilising the growth of the high-admixture market [RE- > STC].

Meanwhile, progress was made with the 2G technology projects [+STC]. The demonstration projects were seen as successful, and the technologies were deemed ready for commercial application [+SPF]. Uncertain market prospects due to the planned changes and frequent adjustments to the policy mix had negative interpretative effects on potential customers, thus signalling political instability [-IntE, -RE]. This mobilised potential domestic customers to advocate for long-term policy design [-SPF, -AF] (Interview 5). However, this feedback was not acted upon by the Swedish government. Comparable global market and political uncertainties [ExC] and the aftermath of the financial crisis [ExC], put a swift end to planned projects with international customers [-STC]. During this phase, only the tall oil hydrotreatment project (Sunpine) could commercialise, while the research into large-scale biomass (Gobigas) and woody ethanol (Sekab) continued [+STC]. At the same time, though, the previously funded actor networks working with the BLG and woody ethanol demonstration projects now faced financial difficulties [-STC]. Still, the technological promise was kept alive [+SPF] and fuelled by a debate on the tax revenues that had already been invested in the various technology projects [-FF]. Thus, both projects were taken over by research actors[8] [+RE]. Additionally, the government established the Swedish Gasification Centre to further coordinate and support domestic biomass gasification R&D [+InsE].

Meanwhile, problems emerged for Sweden's domestic biofuel producers [STC] (Interview 1). The producers opposed the political plans to remove the customs tariffs introduced in 2006 [PMC]. Increasingly global supply and trade, plus upcoming changes in EU legislation (double counting) led to major overcapacity and price dumping in Europe and elsewhere [ExC]. This triggered the European Commission to introduce temporary protective tariffs [ExC]. In 2010, new EU rules opened the way to higher proportions of biofuels in petrol and diesel [ExC]. Responding to the peak in anti-biofuels discourse, the European Commission acknowledged these problems and started to update its legislation (RED) [ExC].

In Sweden, there was growing opposition to the policy mix and, in particular, the tax exemption. An evaluation by the Swedish National Audit Office (RiR 2012:2) found Swedish climate policy to be ambitious but ineffective [-SPF], with unclear and often contradictory goals [-AF]. Moreover, an evaluation of the biofuel taxation system (RiR 2011:10) focused on the high cost of the tax exemptions [-FF]. This negative feedback put the government under increased pressure to change its policy. However, the government remained positive about the technological future of the 2G technologies [+IntE] and launched a public inquiry into "fossil fuel independence in road transport" (Government Bill 2008/09:162) to outline a plan for reaching the target of a fossil-free vehicle fleet by the year 2030 [PMC]. Another investigation pertaining to the introduction of a blending quota was therefore launched. This was undertaken by the Swedish Energy Agency in 2009 (ER 2009:27), and concluded that such a quota would be an important instrument in reaching the EU 2020 target [-SPF]. As a result, in the spring budget bill of 2012, the Swedish parliament decided to introduce a blending quota in 2014 [PMC]. However, the new instrument was withdrawn shortly before its implementation because, having communicated with the EC, the government concluded this quota could not be combined with the carbon tax exemption under the prevailing state aid rules [ExC] (Interview 3) [-IntE], [-AF, -SPF].

5.1.4. Phase 4: 2014–2018

In 2014, a newly elected minority government decided to continue with the existing tax exemption system, as this had been granted by the EC with some modification. This time, the taxes levied on carbon and energy were based on annual adjustment of the taxation levels to avoid overcompensation (Interview 3, Table A3). In practice, this meant that the tax levels had to be adjusted once or twice a year [PMC]. This, in turn, created market uncertainty [-RE], signalling a lack of political commitment and creating a lack of certainty for industrial investors [-IntE].

The taxes induced "panic" in major sections of the industry [-IntE]. 1G producers were also put under additional pressure from changes to the EU legislation (not least the "ILUC Directive"). This legislation introduced a 7% cap on 1G biofuels in the total fuel mix that counted towards the EU 2020 steering targets [PMC], which limited market prospects [-RE]. These changes were interpreted as the end of the high-admixture ethanol market [-IntE], with sales of E85 decreasing by 22% in 2014 (Fig. 3) [-STC].

As a result, only actors working with HVO could be granted full tax exemptions [+RE]. This resulted in a rapid market growth for HVO [+STC], thereby taking increasing market shares from biodiesel (FAME/RME) [-STC]. The profitability of domestically produced ethanol also came under strain [-SPF]. Due to the successful market launch of HVO, the oil refiner Preem (co-owner of the HVO-Sunpine project) made huge promises about the future potential of the technology [+SPF]. However, as HVO has a limited resource base, expectations shifted towards a novel liquefaction process. This involves converting lignin, a by-product of the pulp industry which is available in large quantities [+IntE] (Interview 1) (Fig. 2).

Significant expectations were created around the novel liquefaction process [+SPF] by the actor network. This led to a SEK 71 million grant [+RE] to construct a pilot plant [+STC] (Interview 1) and funding of a SEK 36 million strategic innovation project on lignin for transportation fuels and chemicals.[9] This signalled political commitment [+IntE, +RE] and, in turn, induced positive spillovers to other industry actors [+STC]. Several new entrants were attracted, resulting in prolific experimentation with related technological approaches [+STC] (Fig. 4). However, the promise of these combined concepts meant a severe reduction in funding for the BLG and methane projects [-RE] (Interview 1). While the technological promise was kept alive [+SPF], a lack of private investment finally led to the BLG and methane (Gobigas) projects being halted [-STC].

Meanwhile, the global sense of climate urgency intensified with the Paris Agreement in 2015 [ExC]. Sweden set the target to attain net zero greenhouse gas emissions by 2045 (in force since 2017). The new Swedish climate law included a separate milestone target for greenhouse gas reduction to 70% of previous (2010) levels for the transport sector by 2030[10]. To reach this target, a mix of more efficient vehicles, switching to alternative fuels and behavioural changes was envisaged.

After the success of electric vehicles in neighbouring countries, stronger advocacy also emerged in Sweden [ExC] (Fig. 4). However, the biofuel industry actors argued that all-renewable alternatives were needed [+SPF], and called for additional resources to accelerate technological development [+SPF]. Several industry actors stated that they were ready to make the necessary investment for Sweden to reach its goals [+SPF] but argued that the policy goals were not ambitious

[8] However, the plan that received SEK 500 million in funding from the Swedish Energy Agency was terminated.

[9] The innovation project, called "BioLi2.0", ran from 2016 to 2019 and consisted of 22 research partners from industry, research institutes and academia.

[10] In 2017, the transport sector accounted for about one third of Sweden's greenhouse gas emissions.

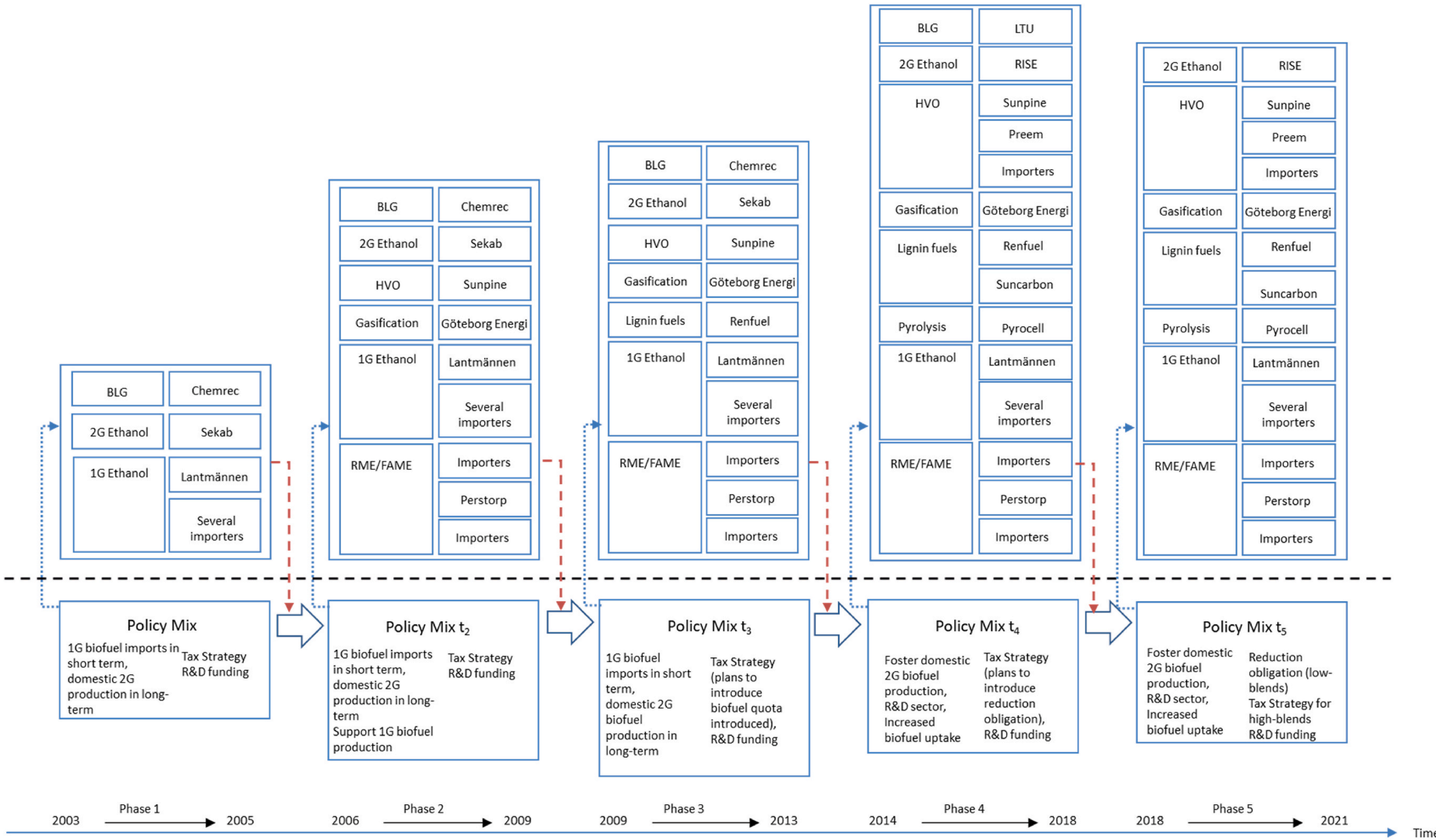

Fig. 5. Synthesis of the main policy effects and feedback in the emergence of the Swedish biofuel industry.

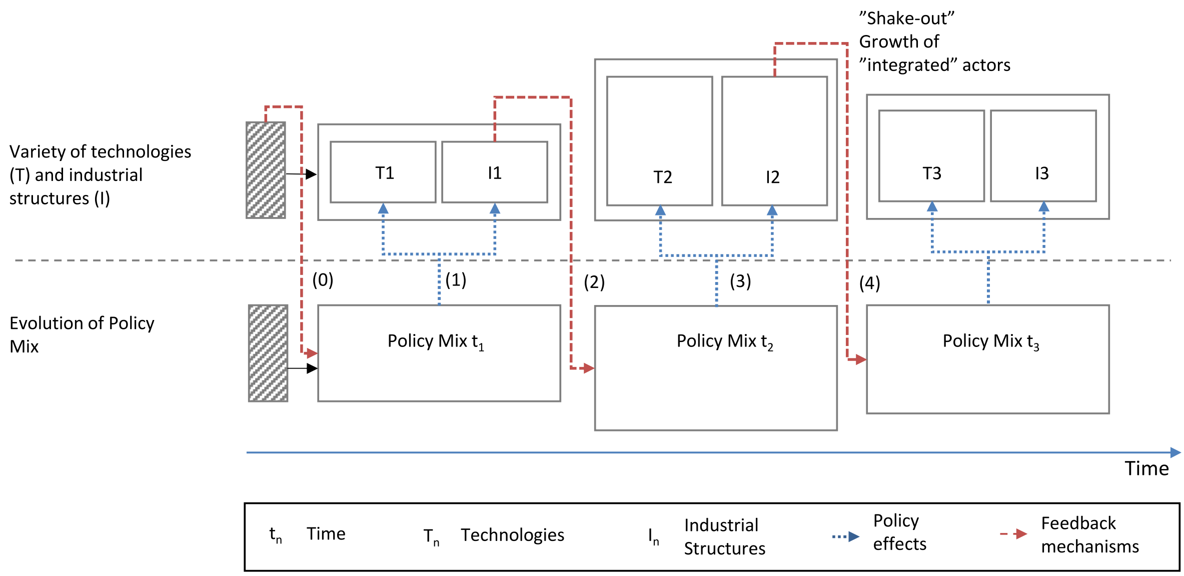

Fig. 6. Stylised process model of the role of policy feedback in the emergence of policy mixes, technologies, and industrial structures leading to domestic green industry growth. The red arrows mark the dominant policy feedback dynamics: (0) feedback from existing actors shape policy mix design, (1) policy effects influence technology and industry structure, (2) feedback from technology and industry structure lead to frequent adjustments of the mix, (3) adjusted policy mix creates uncertainties, influences evolutionary dynamics within a system and brings about a dominance by major new actors, and (4) feedback from these new actors affects policy mix changes.

enough and the instruments not stable [-SPF]. This drive by industry coincided with political pressure to reach the 2045 reduction target [ExC]. Hence, the government tasked the Ministry of Enterprise and Innovation with preparing to replace the taxation system (Interview 3).

With the promise of upcoming political changes, high expectations for a future domestic industry were created by novel 2G actors [+SPF]. However, the existing 1G producers got into difficulties. Low crude oil prices and higher taxes caused financial problems. This, in turn, made them advocate for political support to save the investments that had been made and the jobs that had been created [-SPF]. Nevertheless, their feedback remained largely unacknowledged by the government [-PMC]. Instead, policy changes in Germany [ExC] provided a market for the 1G producers, thus ensuring their future [+RE]. There was further negative feedback on the increased imports of HVO [-SPF], as the negative environmental impacts of palm oil production became globally apparent [ExC]. The domestic HVO producer Preem (which did not rely on palm oil) and some NGOs advocated for a ban on palm-oil-derived fuels [-SPF].

5.1.5. *Phase 5: 2018–2021*

Due to the negative feedback and the policy activities that were introduced at the end of the last phase (Interviews 3, 5), the government introduced a stipulation that fuel suppliers must reduce their greenhouse gas emissions content of low-admixture fuels by annually increasing levels [PMC]. Although aimed at 2030, the annual levels were first rolled out for 2018–2020 because of outstanding changes in EU biofuel legislation (RED II, LULUCF) (Interview 2). For the high-admixture market, the full relief from carbon and energy taxation was given a short-term extension [PMC]. The Swedish government also introduced new sustainability requirements, leading to changes in the calculation of GHG emissions for PFAD-derived biofuels. This was designed to make it less attractive, thus indirectly stimulating domestic production (Interview 2).

The changes implemented in the now separate policy-induced markets for low and high blends shifted the profitability of the different fuel types [RE]. The most notable change concerned HVO, which was now supplied mainly on the low-admixture market to fulfil quota regulations (as it allows for high-admixture quotas). Hence, market shares re-opened for imported and domestically produced 1G biodiesel (Interview 4). However, several industrial actors interpreted the short-termed design of the reduction obligation as a lack of political understanding [-IntE] (Interviews 5,11). During this period, only the existing HVO producer invested in expanded production capacity [STC]. It was only in late 2019 when the blending levels of the reduction obligation until 2030 were rolled out, that new industrial projects were decided upon (Interviews 10, 11).[11]

In parallel with the legislative process, progress was also made in technological development. A collaboration project between Renfuel, Preem and the pulp and paper company Rottneros, was able to progress the furthest. Still, although the legislative situation had improved, the collaboration came to a stop since no agreement could be reached between resource requirements and profit distributions (Interviews 1, 5).

While the national policy up to 2030 has been rolled out, several exogenous factors have started to create new uncertainties. For example, as part of increasing EU climate policy ambitions (the EU Green Deal), plans were announced to phase out combustion engine vehicles by 2035 [ExC]. This introduced uncertainties into the prospect of producing liquid fuels. As a result, the biofuel industry actors perceived the policy mix as too weak to achieve the targets and provide the necessary conditions for making large-scale investments [-SPF]. Acknowledging these concerns, the government commissioned the Swedish Energy Agency to investigate whether there was a need for further policy instruments to address investor uncertainties and stimulate domestic biofuel

[11] One project, Pyrocell, concerned pyrolysis (syngas) (Interview 10) and the other HVO production. However, for the HVO project (by the Finnish-Swedish oil refiner St1), global policy developments also played a strong role (Interview 11).

production [PMC].[12]

5.2. Synthesis

The historical analysis of the evolution of biofuels in Sweden has shown that the country's policy mix has stimulated the emergence of a wide range of technologies and industrial structures, and that actors representing these technologies and industrial structures have in turn influenced policy mix development to varying extents. Overall, the results indicate dynamic complexities underlying the stimulation of technologies and industrial structures, as well as the development of the Swedish policy mix. Building upon our analytical framework, we further synthesise the case description to unravel the underlying processes and mechanisms. Fig. 5 provides an overview of the Swedish case. Combined these results provide new insights into the role of Swedish policy development for domestic industry growth.

During the first phase, the policy mix produced several different policy effects and feedback. Policymakers deemed the deployment of imported biofuels to be the most cost-effective solution to fulfil short-term targets. Hence, the changes implemented in the carbon taxation system induced a rapid market growth in the distribution and end-using sectors. However, the higher-than-anticipated market growth exceeded existing market volumes, leading industry actors to advocate for the ratcheting-up of existing demand-pull instruments to stimulate a domestic production of second-generation biofuels. The growth of imported biofuels also had an immediate spillover effect on the economics of the domestic 1G ethanol producer, prompting it to oppose tax exemptions for imported ethanol. Policymakers also sought to explore technological approaches to converting domestically available forest resources. Thus, they granted substantial public funds to existing research networks for various R&D activities.

The policy mix changes that were implemented in the second phase produced positive effects, which induced growth for importers and fuel sellers. The implemented changes also provided a market for domestic 1G biofuel producers, leading to an expansion in further production capacity. However, rising global feedstock prices hampered the economics of domestic production, which, in turn, closed the window for 1G biofuels, and no more projects were created. Moreover, the policy mix produced positive effects on the development of different technological designs. However, the broad variety of technological alternatives was also interpreted by the industry as a lack of political guidance regarding the preferred technological choices.

During this third phase, the industrial dynamics were characterised by high volatility and uncertainties stemming from political developments in Sweden and internationally. Importers and fuel sellers continued to grow while the economics of the domestic 1G biofuel projects were weakened. Positive resource effects induced continuous R&D work, and while several technologies were considered ready to commercialise, only the Sunpine HVO project was able to materialise on a commercial scale.

During the fourth phase, policymakers started to address the problems related to the demand-pull instruments, both in response to industry stakeholder feedback and to promote domestic production. In anticipation of the changes, the policy mix created positive interpretative effects for biofuels in Sweden, which revived business interest. In addition, the policy mix provided additional resources for technological development, leading to experimentation with different technological designs. The main feedback during this phase related to the design of the demand-pull instruments as well as to the amount of resources for technological experimentation.

While the political conditions concerning biofuel production stabilised during the fifth phase, in Sweden (and internationally), the innovation dynamics of the competing electric vehicles and global climate policies created new uncertainties for actors within the domestic biofuel industry. Although the newly implemented demand-pull instrument for low admixture fuels provided some political stability, few projects materialised during this phase.

6. Discussion

This section is divided into two parts. The first part discusses the empirical findings by deriving a process model and elaborates the research implications. The second part moves on to derive lessons for national policymakers.

6.1. Implications of policy feedback for domestic green industrial growth

The case of biofuels in Sweden illustrates the importance of analysing how policy mixes, technology and industrial structures co-evolve to understand domestic industrialisation processes. By investigating the mechanisms that drove this development in the Swedish biofuel case, the paper illustrates the central importance of policy feedback in developing the policy mix, biofuel technologies and the industrial structure. The findings show that the Swedish policy mix has been established based on the feedback from different pre-existing actor networks, and has adjusted in response to feedback from industrial actors, Additionally, these findings suggest that the Swedish policy mix has been adjusted based on learning effects among policymakers and changes in interlinked policy requirements. As expected, this paper found that multiple policy feedback loops occurred in parallel and sequence. These policy feedback loops differed in two respects. First, the complexity of the technology and industrial structure involved in the different policy feedback loops varies substantially, ranging from few actors and drop-in biofuels to complex actor networks and advanced technologies. Second, the actors involved in the different policy feedback loops have different abilities, capabilities, and interests to participate and influence the policy subsystem and the subsequent policy mix changes.

On a more conceptual level, the paper offers a broader explanation of domestic industrial development by specifying the mechanisms that underlie the dynamic nature of industrialisation processes. In particular, drawing on the innovation systems literature [17], a process model is proposed that refines the existing knowledge of the evolution of industries through the lens of innovation systems. Fig. 6 presents a stylised overview of how policy mixes, technology, and industrial structure co-evolve in domestic industry growth and over time (t). As illustrated in this figure, the evolution of a novel industry is driven by the implementation of a policy mix in time period t_1 (PM t_1). The design of this policy mix is typically influenced by both existing policies and pre-existing actor networks (0). The policy mix affects experimentation with the technological variants and the entry of actors. As illustrated in the empirical case, these activities are well aligned with the existing institutional context, namely R&D activities for collaborative R&D programmes and public research grants and imported renewable energies for the created markets. In response to policy feedback, frequent adjustments of policy instruments seem to occur (2) to increase the complexity of the policy mix over time. However, this comes with a higher risk of inconsistencies.

The uncertainties created by the policy mix (3), in combination with increasing competition between various technological variants, subsequently lead to the "shake out" of actors and technologies [17]. At the same time, intense learning processes occur in the innovation system, and this results in a growth of "integrated actors". The results point towards a special positioning of some actors in the system through, for

[12] The result of the investigation is still pending at the time of writing this paper.

example, their access to key resources such as refining infrastructure. This gives them the ability to shape the selection of technological variants and induce others to act in certain ways. In turn, these actors tend to influence policy mix changes to their benefit (4), while those that cannot adapt retreat.

Compared with past research on policy feedback in context of sustainability transitions [21], the findings reveal complex, heterogeneous policy feedback dynamics. Such differences may be explained by the underlying theoretical concept. Building on the work of the transitions literature, past policy feedback studies explain co-evolutionary dynamics as alignment processes, and suggest that positive or negative dynamics could emerge [42]. Since the present paper is grounded in an evolutionary-based explanation of innovation processes, there is stronger emphasis on the dynamic relationship between industry-level variation and selection (see also [17]). This implies a more explicit consideration of innovation processes at the actor level, plus the complexities arising from the variety of actors, products and technologies involved. The findings highlight the diversity and changing nature of the roles of actors in innovation processes, but also differences in the ways actors and actor groups interact with institutions and policymakers.

This paper tries to explain the dynamics of domestic green industrialisation processes. Complementing past studies on the growth of innovation systems for industrial development in national contexts [6,67,68], the proposed process model provides novel insights into the evolutionary dynamics between policy mixes and the domestic technology, firms and industrial structure. By focusing on the mechanisms through which these processes co-evolve, the model describes concrete effects on the evolution of domestic technology and industrial structure, driven by dynamic policy mix changes over time.

Whilst the present analysis has only examined a single case study, it can be expected that the observed policy feedback dynamics are transferable to other countries and, presumably, other technological fields. For example, previous research on biofuels in Finland showed an earlier entry of incumbents, and this, in turn, significantly shortened the first phase of variety creation and experimentation [14].

The main value of this paper lies in providing an in-depth understanding of the co-evolution of policy mix, technologies, and industrial structures in the context of green domestic industry growth. The findings emphasise that achieving the dual national policy goals of deployment of renewable energies and domestic industrialisation requires actors that are capable of driving technological change and influencing the relevant policy processes. Generally, innovation systems encompass a wide variety of actors, such as manufacturers, producers, distributors, or research providers, that differ according to their expectations and visions [26,31].

The empirical findings point towards a relative bottleneck of capable actors that can fulfil a wide range of activities within systems. The capabilities of smaller actors are typically limited to specific aspects of innovation and deployment processes, such as R&D work or product imports. By contrast, larger actors, including multinationals, tend to have greater capacity to realise the necessary industry projects and participate in policy processes; yet they could be more hesitant to enter a new industry. This ties in with past research highlighting the limited abilities and interests of incumbents to support sustainable industrial development [69]. Furthermore, the findings highlight the role of timing between policy mix changes, technologies, and firm behaviour. Overall, this paper stresses the importance of considering innovation processes at the micro-level of actors, plus mutual interdependencies between actors and policy mixes in future research.

6.2. Implications for policy development

This paper suggests that the literature on policy feedback and related discussions on policy design provide useful starting points for deriving lessons about policy. To overcome path dependencies and political constraints in the evolution of policies and foster technological change, policy feedback scholars have proposed a discussion on the *inversion* of path dependencies in policymaking [23,24]. It has been argued that policies can be intentionally designed to be sticky, and that support gradually increases with key target groups [23]. Such policies have been argued as important when it concerns constituency-building for climate policies and accelerating transitions [70]. These arguments are discussed below in the light of the empirical findings and theoretical implications.

First, as shown in the empirical case study, how policy effects are distributed and sequenced could strongly influence how actors structure their activities, which technologies can progress over their lifecycle and which products gain market shares. This demonstrates that policymakers can shape, to a certain extent, how domestic industries evolve within innovation systems. The findings also demonstrate profound differences in the capabilities, abilities, and resources of actors to produce policy feedback, resulting in a diverse set of self-reinforcing dynamics. Hence, the analysis suggests that policymakers would benefit from government-level capacity (in terms of knowledge about industry) to adjust the policy mix to: the domestic industry context; the technology and industrial structures they can realistically foster; and the characteristics of the actors involved.

Second, the case study adds to the conceptual debate around constituency building. Contrary to prior studies concluding that "the more green industries form or expand, the stronger coalitions for decarbonising energy systems become," [[71], p.1171], the findings of this paper illustrate that, as needs for policy interventions differ substantially across actors, technology and industrial structures, policy feedback dynamics can become rather scattered as time passes. These findings match those observed in some earlier studies. Smith [72] suggests that actors develop different policy preferences over time. Similarly, Gomel and Rogge [15] found that competing actor coalitions advocated for opposing policy mix adjustments. Consequently, this paper suggests that policymakers should become more aware of the reversed effects of policy feedback on actor strategies and behaviour in sustainability transitions.

7. Conclusions and avenues for future research

Responding to stringent global climate policies, governments are increasingly voicing the ambition to combine the required transformation of the energy system with the growth of domestic industries. To this end, national policymakers often implement innovation policies to promote emergence of different technologies and industrial structures in parallel. Although recent research has shown that the design and sequencing of policy mixes required to promote such technologies and industrial structures can differ widely, it remains rather unclear to which extent policymakers can address such varying needs in the context of politics and path dependencies. To address this research gap, this paper seeks to enrich current understanding of the role of policy development in the emergence of domestic green industries. Using the case of biofuels in Sweden, it addresses the following interlinked research questions: (1a) how the policy mix development has affected the emergence of technologies and industrial structures, and (1b) how actors associated with different technologies and industrial structures in turn have influenced the development of the Swedish policy mix.

Building upon the historical case analysis, it is argued that that the policy mix has fostered a range of different technologies and industrial structures, whereas mainly imported biofuels and small-scale technology developments could be retained (1a). The findings have also shown differences in the abilities, motivations, and capabilities of actors to influence the Swedish institutions and the adjustment of the biofuel policy mix (1b). These findings point towards an important role of policy feedback for the development of the Swedish biofuel industry structure. More broadly, it implies that the opportunities for national policymakers to shape the emergence of technologies and industrial structures decline as a new industry matures. By incorporating ideas from policy feedback theory, the paper contributes with a novel process model to prior innovation system studies addressing the impact of policy mixes on the value chain formation and industry localisation. Moreover, there are lessons for national policymakers who wish to stimulate and steer technology, firms, and industry structures in national contexts.

Finally, it can be argued that the main limitation of this paper is the limited geographical scope. As the scope of the current investigation was limited to the case of Sweden, future research should concentrate on investigating policy feedback dynamics in the EU, including at Member State level. Another promising avenue for future research should be to expand the analysis to the emergence of competing technological solutions, i.e., biofuels versus electrification. Research that addresses the interplay between different technology-specific policies, such as biofuel and electrification policies, could be particularly fruitful.

Credit author statements:

Barbara Hedeler: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. Hans Hellsmark: Conceptualization, Visualization, Writing – review & editing, Supervision, Funding acquisition, Project administration. Patrik Söderholm: Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The interview data that have been collected are confidential.

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Appendix

Table A1
Overview of archival data.

Document type	Major data sources
Documents on policy strategies and instruments	Database of the Swedish Parliament, written laws, commissions of inquiry
Documents on policy processes	Database of the Swedish Parliament, written communications from the Riksdag, records and statements of opinion, etc.
Documents on industry developments	Websites of Swedish Energy Agency, the industry organisation f3, industry trade journal “The Digest”

Table A2
Overview of the interview sample.

Actor type	# Interview	Description
Policymakers (incl. civil servants)	1	Staff at RD&D funding organisation
	2	Policy officer at ministry
	3	Policy officer at ministry
Industry associations, producers	4	Industry association
	5	Potential customer of technological developments
	6	Raw material producer/technology developer
	7	Car Manufacturer 1
	8	Car Manufacturer 2
	9	Biofuel producer/distributor
	10	Technology manufacturer
Research, consultants	11	Consultant
	12	Consultant

Table A3
Overview of the main elements of the Swedish biofuel policy mix.

Year	instrument	Design features			Reference
2002	Taxation strategy for biofuels	Pilot projects	Full deduction of energy and carbon tax		2002/03:1
		Other biofuels	Full deduction of carbon tax		
2004	Taxation strategy for biofuels	Pilot projects	Full deduction of energy and carbon tax		2003/04:1
		Other biofuels	Full deduction of energy and carbon tax		
2006	Customs tariffs for ethanol imports	Import as chemical product (KN-nr 3824 90 99), import of E85 and ED95	6.5% of goods value		Swedish Energy Agency 2009
		Import as undenatured ethanol (KN-nr 2207 10 00), for low admixture	EUR 19.20 per 100 l		
		Import as denatured ethanol (KN-nr 2207 20 00), production of E85	EUR 10.60 per 100 l		
2006	Fuel specification diesel	5% admixture of FAME in biodiesel (before 2%)			Proposition 2005/06:181, betänkande 2005/06:MJU28, riksdagen skrivelse till regering 2005/06:345
2013–2017	Taxation strategy for biofuels	Ethanol in benzine	89% deduction, taxation cap on 5%	01/01/2013	Swedish Energy Agency 2014
			79% deduction, removal of 5% taxation cap	01/12/2015	Swedish Energy Agency 2016
			74% deduction	01/01/2016 to 01/06/2016	Swedish Energy Agency 2016
			88%	01/08/2016 to 31/06/2018	Swedish Energy Agency 2018
		ETBE (Ethyl tert-butyl ether) in benzine (biobased share)	89% from energy tax	01/01/2013	Swedish Energy Agency 2016
			100%	01/12/2015 to 30/06/2018	Swedish Energy Agency 2018
		Ethanol in E85 (flex fuel)	78% from energy tax	01/12/2015	Swedish Energy Agency 2016
			73% from energy tax	01/01/2016	Swedish Energy Agency 2016
			92% from energy tax	01/08/2016	Swedish Energy Agency 2016
			100%	01/01/2018	Swedish Energy Agency 2018
		Ethanol in ED95 (95% bio-ethanol)	100%	–	Swedish Energy Agency 2016, 2018
		FAME (Fatty acid methyl esters)	8%, volume cap		Swedish Energy Agency 2016
			8% energy tax, removal volume cap, limited in practice through 7% fuel standard	01/12/2015	Swedish Energy Agency 2016
			36% deduction from energy tax	01/08/2016	Swedish Energy Agency 2016
		B100 (neat biodiesel)	44% deduction energy tax		Swedish Energy Agency 2016
			50% deduction energy tax	01/01/2016	Swedish Energy Agency 2016
			63% deduction energy tax	01/08/2016	Swedish Energy Agency 2017
			100% from both energy and carbon tax	01/01/2018	Swedish Energy Agency 2018
		HVO (Hydrotreated vegetable oil)	100% reduction of energy tax, volume cap to 15%	01/01/2013	Swedish Energy Agency 2014
			100% reduction of energy tax, removal of volume cap	01/01/2014	Swedish Energy Agency 2016
2018	Greenhouse gas reduction obligation for low-admixture biofuels (2018–2020)	Benzine: 2,6% in 2018, 2,6% in 2019, 4,2% in 2020	Fines: 4kr/kg CO_2 equiv.		2017:1201
		Diesel: 19,3% in 2018, 20% in 2019, 21% in 2020	Fines: 5kr/kg CO_2 equiv.		2017:1201
2018	Taxation strategy for pure and high blended biofuels	Pure and high blends	100% relief	2018 to 31/12/2020	Swedish Energy Agency 2019
2020	Greenhouse gas reduction obligation for low-admixture biofuels (2020–2030)	Benzine: annual increase to 28% in 2030			Swedish Energy Agency 2019
		Diesel: annual increase to 66% in 2030			Swedish Energy Agency 2019
2020	Taxation strategy for high blended biofuels	Pure and high blends	100% relief	31/12/2020 to 31/12/2021	Ministry of Finance, 2020

Table A4
Overview of the main actors and technology projects involved in different biofuel products (data: Bioenergi (2021); Swedish Energy Agency [73–76], large-scale technological development projects marked with *.

Biofuel	Main actors involved	Year	Capacity	Raw material
Ethanol	Importing companies	2003	n.d.	Sugar-rich feedstocks, i.e., sugarcane
	Domsjö Fabriker (pulp and paper mill)	1910	23,000 m^3	Wood
	Lantmännen (agricultural cooperative)	2001, expansion 2007	50,000 m^3, 230,000 m^3	Cereals
	St1 (oil company)	2017	5,000 m^3	Bakery waste
	Sekab-Rise P* (technology developer/research institute)	2004	133 m^3	Lignocellulosic feedstock
Biogas (in the form of compressed biogas CGB and liquefied biogas LBG)	Göteborg Energi, Gobigas project* (municipality)	2014	20 MW	Forest residue, solid biomass
Hydrotreatment	Kiram/Sunpine (technology developer/Joint venture between tech developer, forest and oil company)	2010, exp. 2018	100,000 m^3, exp. 150,000 m^3	Crude tall oil
	Importers (diverse)	2012	n.d.	Vegetable oils and waste fats
	St1 (oil company)	2019 (online 2022)	200,000 t	Mixed oils
Biodiesel (FAME/RME)	Ecobränsle (agricultural cooperative)	2007	55,000 m^3	Rapeseed
	Perstorp (chemical company)	2007, exp. 2016	160,000, exp. 230,000	Rapeseed
	Importers (diverse)	2006	n.d.	Maize, palm oil, etc.
	Small scale domestic producers (agriculture/farmers)	n.d.	n.d.	Raps, etc.
Syngas	Chemrec-LTU* (technology developer/research institute)	2004	1,800 t	Black liquor
Hydrotreatment-based diesel & petrol (lignin, pyrolysis, hydropyrolysis)	Preem (oil company)	2010, exp. 2015, 2019	100,000 m^3, 160,000 m^3, 210,000 m^3	Mixed oils and fats
	Renfuel (technology developer)	2017	3,000 t	Lignin
	SCA (forest company)	2017	24/ litres/ day	Lignin
	Suncarbon (Joint venture between forest and oil companies)	2017	n.d.	Lignin

Table A5
Keywords used to study knowledge development in fuel types (all „Biofuel*" and „Sweden", 2003–2021).

Biofuel	Keywords
Ethanol	"Ethanol" OR "Bioethanol" OR "Ethanol Production" OR "Bio-ethanol production" OR "Cellulosic Ethanol"
Biogas	„biogas" OR „Methane" OR „anaerobic AND digestion"
Hydrotreatment	„Hydrotreatment" OR „vegetable oil" OR „hydrogenation"
Biodiesel	„Esters" OR „Transesterification"
Syngas	„Syngas" OR „Pyrolysis" OR "biooil" OR "thermal" OR "gasification"

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