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Future ecosystem business model tool: Design science and field test in the efuel ecosystem towards the sustainability transition

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ABSTRACT

This paper presents a novel business model design tool called *Future ecosystem business model (FEBM)*. The FEBM aims to address the lack of managerial tools linking business models, foresight, and ecosystem strategizing in the context of systemic technological changes, as those characterizing the sustainability transition in a multi-level perspective. The tool has been shaped through a design science approach building on a structured review of the literature. A field test was conducted through a case study to test the proposed tool. The empirical context was that of a publicly funded project in the field of electrofuels (efuels). The project foresaw the development and integration of several technologies, whose adoption was likely to have significant implications within and across industries. The proposed approach contributes to the literature on business model design in the context of technology-driven transformations characterized by high uncertainty and interdependence, such as those related to the sustainability transition. Strategy and innovation managers may find in the proposed FEBM tool an actionable approach to shape decision-making against far-reaching technological and societal challenges.

1. Introduction

Whenever systemic changes are required, technology is just one aspect to consider alongside many other system elements which are complex in nature and encompass technological, environmental, social, political, and economic factors (e.g., Huijben et al., 2016; Hess, 2014). This is the case of sustainability transitions, namely “shifts towards more sustainable modes of production and consumption” (Markard et al., 2012). These indeed entail long-term, multi-dimensional, and fundamental socio-technical transformations characterized by significant uncertainties within and across domains (Andersen & Markard, 2020; Geels et al., 2020; Nyangchak, 2022). In these contexts, it is likely that new interdependencies arise well beyond existing industry boundaries, establishing links with remote value chains with different value propositions, actors, and market objectives (Bergman et al., 2019). Firms are thus prompted to intervene on their existing business models, while latent or new business models might emerge (Wesseling et al., 2020). Sustainability transitions thus not only require managers to recognize the urgency of change, but also that the company strategy is proactively defined and located in a changing ecosystem (De Haan & Rotmans, 2018). Managers are becoming increasingly aware of the importance of a good understanding of their current and prospect business ecosystems to keep up with—and stay ahead of—the pace of change. Therefore, “ecosystem strategizing” (i.e., engaging critical actors to deliver compelling value propositions; Adner, 2017) is needed to address the complexities and challenges associated with inter-organizational design and long-term relationship viability (Clauss & Ritala, 2023; Shen et al., 2024).

In the existing literature on sustainability transitions, significant effort has been dedicated to enhancing the understanding of policy actions and their implications (Bergek et al., 2023; Scoones et al., 2020; Smith et al., 2005; Trotter & Brophy, 2022). Recently, there has been an increased focus on organizational agency under the Multi-Level Perspective (MLP) on sustainability transitions (Geels, 2002, 2020; Turnheim & Geels, 2019). This has led to investigations on business model design and ecosystem evolving structures within these contexts, whereby internal alignment and external viability seem equally important forces (Kurucz et al., 2017; Walrave et al., 2018; Wesseling et al., 2020). However, despite this growing attention, the development of frameworks and tools to support managerial decision-making has lagged behind. As increasingly recognized within the academic community (Aguinis et al., 2014; Starkey et al., 2004), there is a need for a closer link between research and practice, as “[…] *understanding a problem is only halfway to solving it*” (van Aken, 2004, p. 220).

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When approaching business model design, managers can leverage a range of established processes and frameworks (i.e., business model design tools) that help creativity and systematization in the initial phase of development, exploration, and assessment of alternative approaches (Baden-Fuller & Morgan, 2010). Yet, existing tools seem not adequate in the context of sustainability transitions, since they do not allow a reflection from a MLP perspective and project fluxes of value embedded in still-evolving ecosystem relationships. A new logic of analysis and evaluation is thus needed for two main reasons. First, most business model design tools are still based on a static view of the context external to the firm (Athanasopoulou and De Reuver, 2020). This represents a major limitation considering the uncertainties characterizing the environment where firms operate. Due to limited incorporation of future-oriented thinking, the generation and evaluation of alternative scenarios are hindered (e.g., Fritscher & Pigneur, 2014; Remane et al., 2017). Second, while business model design tools map external influences and interactions, they mostly overlook the strategic options for ecosystem design, neglecting the active role firms can play in shaping their network of relationships. In this way, they do not allow for a concurrent definition of the business models of multiple parties for interdependencies (Shipilov & Gawer, 2020; Kapoor, 2018; Adner, 2017). Both aspects are obviously crucial for firms in transitioning to sustainability.

Given the lack of tools addressing the uncertainties and interdependencies of sustainability transitions, this study proposes a method—named *Future ecosystem business model (FEBM)*—to systematically shape strategic questions and decisions on a firm's business model through the structured application of a *foresight logic* (to address uncertainty) and an *ecosystem logic* (to address interdependencies). The FEBM was built through a design science approach, namely leveraging scientific knowledge to produce a theory-grounded and field-tested managerial tool for an emerging class of managerial issues (Hevner et al., 2004; Hevner, 2007). Taking steps from the MLP, the FEBM was built for problem contexts characterized by uncertainty and coevolutionary interdependencies thanks to the integration of concepts and approaches drawn from different literatures (e.g., business model design tools, ecosystem strategizing, sustainability transition, scenario planning) (Adner, 2017; Athanasopoulou & De Reuver, 2020; Magretta, 2002; Markard et al., 2012; Nowack et al., 2011). The proposed tool was tested, refined, and validated through the development of a case study in the context of a publicly funded project in the field of electrofuels (efuels). The case proved particularly relevant due to high uncertainty in terms of technological development, social acceptance, economic convenience, and policy support. Moreover, it was characterized by interdependencies among project partners and other firms possibly involved in the emerging ecosystems (e.g., complementors and customers). The tool can be used by managers operating in contexts characterized by uncertainty and coevolutionary interdependencies.

We trust that managers can find a proven methodology in the FEBM tool to update and rethink their decision-making process and related analytical phases. Through a set of techniques to anticipate and imagine scenarios, trends, and discontinuous changes, it facilitates strategic reasoning around alternative futures while allowing managers to safely experiment, fail, and learn about the opportunities at hand (Rohrbeck et al., 2015). Against the ever-increasing environmental dynamism and complexity, researchers indeed advocate a broader use of scenario-based planning methods (Ginanneschi, 2021; Kunc and O'Brien, 2017). The application of an ecosystem logic further enables an early alignment among firms, which is needed to organize the direction of innovation and define the dynamics of value creation (Stål et al., 2023; Brink, 2022).

The paper is structured as follows. Section 2 presents the theoretical background. The research methodology is presented in Section 3. Then, the conceptual FEBM tool is provided in Section 4. The case study is included in Appendix to allow the reader to the understand the practical use of the tool and the results of our test. The discussion revolves around the theoretical implications and managerial contributions (Section 6). We conclude by outlining the limitations of the study and future research directions.

2. Theoretical background

2.1. Designing business models for sustainability transitions

A business model is described as the set of strategic and organizational solutions with which companies develop competitive advantage reflecting core value propositions (Teece, 2010; De Reuver et al., 2013). Business models can be innovated and transformed (Chesbrough and Rosenbloom, 2002; Markides, 1999) through the discovery or application of new or different business models in already-known industries (Markides, 2006; Pohle & Chapman, 2006). The process is different depending on whether it concerns new ventures (i.e., start-ups or new projects within an established firm) or already-existing firms that need to transform following strategic decisions or external pressures (Afuah & Tucci, 2003). When an innovation occurs, it is always necessary to create, design, and project business models from the point of view of individual firms (Giesen et al., 2007).

With respect to firms' role in sustainability transitions, there is ample agreement on how business model innovation can destabilize existing socio-technical systems, promoting systemic changes in dominant patterns (Boons & Lüdeke-Freund, 2013). Recently, this perspective has been challenged by a deeper understanding of how business models are shaped by looking at contextual opportunities and constraints within the existing socio-technical system, which define the so-called "business model design space" (Kurucz et al., 2017; Huijben et al., 2016). This understanding is mostly grounded in the literature on sustainability transitions, specifically in the MLP (Geels, 2002; Geels & Schot, 2007).

The substantial body of knowledge that, since the early 2000s, has been developing on sustainability transitions stems from the premise that established technologies are deeply intertwined with user practices, complementary technologies and infrastructures, business models and inter-organizational value networks, as well as institutional setups (Markard et al., 2012). In this sense, the concept of socio-technical systems has been used to describe the interplay between the technological sphere and different societal aspects (Andersen & Markard, 2020). Due to far-reaching interdependencies, socio-technical systems are expected to evolve slowly and incrementally, making it crucial to investigate how sustainable modes of production and consumption—such as the shift towards renewable energies—can be promoted and governed (Hess, 2014; Kanda et al., 2021).

The MLP is a rather dominant approach for conceptualizing the interplay between different spheres and levels of a socio-technical system. At its core, the MLP conceptualizes transitions as multi-phased processes across three levels: niches, regimes, and landscapes (Geels, 2002; Geels, 2020). Niches—protected spaces within regimes—are where innovation is developed. Regimes show overall stability in socio-technical components due to a semi-coherent set of rules orienting the actions of social groups. Landscapes are characterized by structural trends, societal values and worldviews, which might change in the long run and influence the rules behind the regime. Depending on niche-regime-landscape interactions, different transition pathways might emerge (Geels & Schot, 2007). Initial criticisms towards MLP were mainly concerned with its overemphasizing structural dimensions at the expense of organizational agency (e.g., Genus & Coles, 2008). These criticisms have been subsequently addressed by suggesting that actors assume a structuring role in terms of evaluating actions, adjusting strategies, and changing resource positions, for example, by gaining higher market share or better resource control (Geels, 2011, 2020). Namely, it has been recognized that actors can combine and reproduce different socio-technical system elements with an impact on the system itself. Here is where micro- and meso-level perspectives can come into play in terms of firms' strategic behavior and inter-organizational

Table 1
Comparison of tools/methodologies.

Model or methodology	Point of view			Notes/ critiques
	Business model	Business ecosystem	Foresight	
Model proposed by (Linder and Cantrell, 2000)	x	o		It is focused on the business model, with a present view and a partial consideration of the ecosystem. It highlights the effects on customers.
e3-value modelling (Gordijn, 2004)		x		It is focused on the business ecosystem, with a present view, without taking in consideration the impacts on the business model.
Value network model of intangibles (Allee, 2000)		x		It is focused on the business ecosystem, with a present view, without taking in consideration the impacts on the business model.
Sense testing map (Voelpel et al., 2005)	x	o		It is focused on the business model, with a present view and a partial consideration of the ecosystem. It highlights the effects on customers.
Model proposed by (Poel et al. 2007)		x		It is focused on the business ecosystem, with a present view, without taking in consideration the impacts on the business model.
Model proposed by (Seelos & Mair, 2007)		x		It is focused on the business ecosystem, with a present view, without taking in consideration the impacts on the business model.
c3-value model (Weigand et al., 2007)		x		It is focused on the business ecosystem, with a present view, without taking in consideration the impacts on the business model.
Agent based methodology (Marin et al. 2007)		x		It is focused on the business ecosystem, with a present view, without taking in consideration the impacts on the business model.
Model proposed by (Kamoun, 2008)	x	o		It is focused on the business model, with a present view and a partial consideration of the ecosystem. It highlights the effects of external forces.
BEAM: business ecosystem analysis and modelling (Tian et al. 2008)		x		It is focused on the business ecosystem, with a present view, without taking in consideration the impacts on the business model.
Triple layer business model canvas (Joyce and Paquin, 2016)	x	o		It is focused on the business model, with a present view and a partial consideration of the ecosystem. It highlights the sustainability point of view.
Model proposed by (Goethals, 2009)	x	x		It is focused on the business model, with a present view and a consideration of the ecosystem.
Business model framework (Hulme, 2010)	x			It is focused on the business model, with a present view.
Business model canvas (Osterwalder & Pigneur, 2010)	x			It is focused on the business model, with a present view.
Lean canvas (Maurya, 2010)	x			It is focused on the business model, with a present view.
Minimum viable product (Ries, 2011)	x			It is focused on the business model, with a present view.
BM service innovation triangle (Furseth and Cuthbertson, 2013)	x			It is focused on the business model, with a present view.
MOBENA: Methodology of business ecosystems network analysis (Battistella et al., 2013)		x	x	It is focused on the business ecosystem, with a future view, without taking in consideration the impacts on the business model.
Model proposed by (Gavrilova et al. 2014)	x			It is focused on the business model, with a present view.
Business model canvas evolution (Fritscher & Pigneur, 2014)	x		o	It is focused on the business model, with a future view related to evolutionary view.
Business Model Navigator (Gassmann et al., 2013)	x			It is focused on the business model, with a future view related to evolutionary view.
Business model pattern database (Remane et al., 2017)	x		o	It is focused on the business model, with a future view related to evolutionary view.
Business Ecosystem explorer (Faber et al., 2018a)		x		It is focused on the business ecosystem, with a present view, without taking in consideration the impacts on the business model.
VTDF (value, technology, distribution, finance) business model (FW, 2023)	x			It is focused on the business model, with a present view.
Business model schema (Kim et al., 2020)	x			It is focused on the business model, with a present view.
Collaborative circular proposition design (Brown et al. 2021)	x	o		It is focused on the business model, with a collaborative view.
Demand response business model canvas (Hamwi et al., 2021)	x	x		It is focused on the business model, with a present view and a consideration of the ecosystem.
BM3C2 (Boldrini & Antheaume, 2021)	x	o		It is focused on the business model, with a present view and a consideration of the ecosystem in terms of 2to2 relationships.
Business ecosystem mapping (Circit nord, 2023)		x		It is focused on the business ecosystem, with a present view, without taking in consideration the impacts on the business model.
Actor roles mapping (Brea, 2023)		x		It is focused on the business ecosystem, with a present view, without taking in consideration the impacts on the business model.
Sustainable by design tool (Coffay & Bocken, 2023)	x		o	It is focused on the business model, with a future view related to sustainability.

Legend: x element taken in consideration; o element taken partially in consideration.

alignment.

When considering individual firms, it has been shown that companies developing innovations for sustainability transitions develop value business models that either "fit-and-conform or stretch-and-transform" the existing regime (Huijben et al., 2016; Wesseling et al., 2020). The first option involves evolving niche products and services that respond to the regime's mainstream selection environment, establishing linkages with existing industry incumbents. Vice versa, the stretch-and-transform approach occurs whenever the paybacks of niche products and services over those of the regime are stressed in order to meet landscape pressures, possibly establishing relationships with new entrants from diverse industries. These different business model design options seem driven by the characteristics of the socio-technical regime in which firms work. Similar considerations have been formulated by Walrave et al. (2018) in the context of interorganizational relationships. Specifically, their study originates from the premise that innovations are increasingly developed and marketed by networks of co-creating actors, namely ecosystems (Adner, 2017; Shipilov & Gawer, 2020). Whereas prior literature has amply stressed the need for actor alignment within the ecosystem (Brink, 2022; Stål et al., 2023), Walrave et al. (2018) draw from the MLP to further theorize about the importance of making the ecosystems' value proposition viable within the broader socio-technical system.

To summarize, recent studies linking business models, ecosystems, and socio-technical systems for sustainability transitions inform some important considerations for the purpose of this study. First, business models take form within a "design space" determined by the current shape of the socio-technical system and evolutionary trajectories stemming from niche-regime-landscape interactions. This requires informing business model design efforts with a view on possible changes within and across different system levels and components, including technology, policy, and culture (*foresight logic*). Second, when considering multi-level interdependencies, firms' interactions within their respective ecosystems should also be considered. Not only do technology development pathways often involve multiple actors with complementary capabilities, but also the promotion of new solutions in established socio-technical regimes demands establishing inter-organizational and cross-industry linkages. For this reason, it is important to formulate and project a possible coevolution of firm-specific business models (*ecosystem logic*). In the next section, we review existing business model design tools to assess their fit with these two requirements.

2.2. Business model design tools

Business models can be represented and conceptualized. In general, most conceptualizations are based on the idea that a business model is a multi-dimensional concept, whereby the definition of each dimension is interdependent on the other ones (Morris et al., 2005; Magretta, 2002). Specifically, business model frameworks might have an economic focus (i.e., describe the revenue and cost components; Al-Debei & Avison, 2010), an organizational focus (i.e., define the firm-specific value proposition and related capabilities; Osterwalder et al., 2005), and a strategic focus (i.e., illustrate the governance choices in interacting with other players contributing to value creation activities; Casadesus-Masanell and Zhu, 2013).

Crafting a business model requires continuous exploration to determine the optimal methods for innovation, uncovering unknown opportunities, or achieving practical goals. Designers strive to push the limits of conventional thinking, generate fresh possibilities, and ultimately deliver value to users (Afuah & Tucci, 2003). This process necessitates envisioning what does not yet exist while taking into account a complex array of factors, including competitors, technology, the legal environment, and more. Increasingly, this exercise can take place in unfamiliar, uncharted territory, characterized by rapid and transformative changes (Liu et al., 2021; Kunc & O'Brien, 2017).

Business model design tools are an important aid to the process, as they channel managerial efforts, business acumen, skills, and knowledge within a structured approach (Massa et al., 2017; Fraser, 2007). Moreover, design tools can be used to share ideas and co-design a business model space. Many academics have indeed highlighted their role in getting "everyone in the organization aligned around the kind of value the company wants to create" (Magretta, 2002). In this sense, tools represent "boundary objects" that facilitate exchanging business model ideas between stakeholders (Bouwman et al., 2018). Their application needs to occur in dynamic conditions as "the system must be shocked out of its inertia" (Giesen et al., 2007).

Table 1 provides an overview of the business model design tools that more closely relate to these challenges, which have been systematically identified. Namely, we performed two keyword searches on Scopus based on article title, abstract and keywords. We looked for "Business ecosystem AND tool/model/framework" and "Business model AND tool/model/framework", restricted to academic journal articles written in English in the area of business management and accounting. This yielded 7568 papers. We then selected the papers based on two criteria: *i)* that they proposed genuinely new tools, models, or frameworks, not merely reused or applied existing ones; and *ii)* that they primarily focused on addressing business model- or business ecosystem-related challenges. To validate our selection, we cross-referenced our results with existing literature reviews such as 'Modelling Business Models' by Breuer et al. (2018) and 'Modelling Ecosystems' by Tsai et al. (2022). Additionally, we integrated our findings with some 'grey literature', including books and insights from experts. We chose to do so because many of these tools originate from practical contexts and hold practical value. Thus, they are more recognized in the consultancy world than in academia. Finally, we analyzed the papers positioning each tool in the business model, ecosystem, and foresight literature.

Our analysis highlights the lack of tools that integrate both the ecosystem and the foresight logic when designing a business model. Specifically, there are gaps in terms of:

- Business model exploration (*foresight logic* in business model design). This aspect is largely underrepresented in the literature, as recently highlighted by Athanasopoulou & De Reuver (2020) in their review of tools that support the initial, exploratory stages of developing new business models, to assist in their initiation, conceptualization, assessment, and planning. This phase is characterized by significant uncertainty regarding offerings and addressable markets, necessitating extensive idea generation, reframing, comparison, and evaluation. Tools for business model exploration should thus include the definition of alternative scenarios and facilitate the formulation of alternative and multiple options. However, the few existing tools that support the generation of multiple business model options do not allow for reasoning in a what-if logic, as foresight techniques are not exploited to generate alternative scenarios in which each option can be evaluated.
- Integration of ecosystem strategizing (*ecosystem logic* in business model design). Established business model tools (e.g., the Business Model Canvas and its elaborations; Osterwalder & Pigneur, 2010; Joyce & Paquin, 2016) take into account the environment external to the firm, including the relationships with other companies and stakeholders, as important features for the subsequent design of the business model. In this sense, these tools assume that firms' choices are embedded in the context where they take place. The context is essentially thought of as exogenous, coming as an input for managerial decision-making. However, the advocates of ecosystem strategizing have explicitly called for a change of perspective as firms can play an active role in shaping the network of relationships (Shipilov & Gawer, 2020). In this sense, "[…] an ecosystem strategy can be thought of as one that takes partner firms' business model to be as critical to address as the focal firm's" (Adner, 2017, p. 51). Within ecosystems, value is, in fact, created by a network of firms, including suppliers, customers, complementors, and competitors (Aarikka-Stenroos & Ritala, 2017). There is a need to explore alignment structures early on to direct ecosystem-level innovation and future cooperation (Stål et al., 2023; Brink, 2022). Yet, current approaches are limited to mapping firms' interactions. Tools that allow the formulation and analysis of the strategic options for ecosystem design are missing.

In sum, current business model design tools reduce the managerial task to firm-level value creation, delivery, and capture rather than enabling the joint definition of the firm's and partners' strategic options. When considering sustainability transitions, there is instead the need of practical approaches for companies to "play the ecosystem game", especially considering different scenarios. Such approaches would allow the formulation of alternatives, as interdependence and integration challenges create uncertainties beyond the familiar risks of managing new ventures (Kapoor, 2018; Adner, 2006). Whereas these aspects are increasingly focused in academic studies, especially in those addressing sustainability transitions from the MLP (e.g., Geels, 2020; Wesseling et al., 2020), conceptual advances have not led to an update of existing tools. In this respect, a foresight logic can guide the process through the

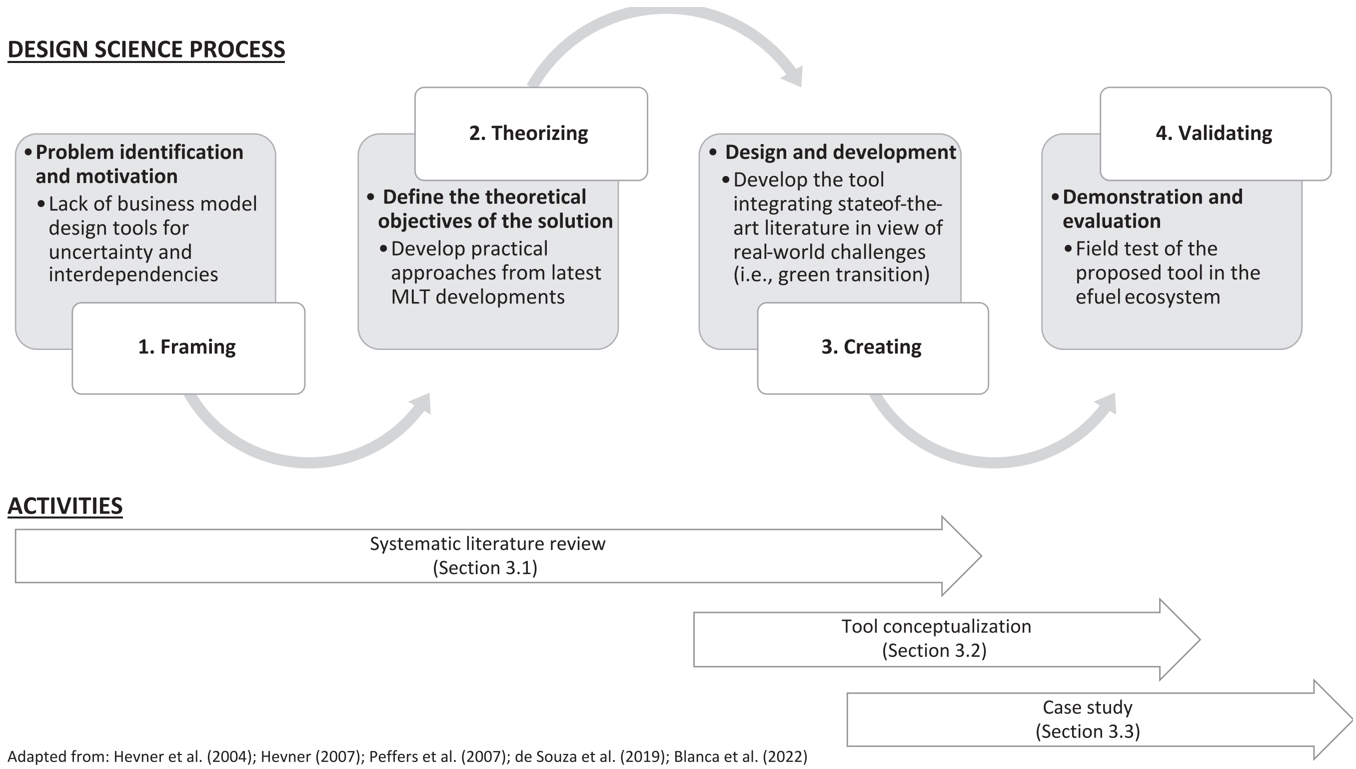

Fig. 1. Research process.

complex and interrelated elements defining the environment where the ecosystem takes shape.

Our research thus attempts to answer the following research question (RQ): *How is it possible to design future-oriented business models in emerging ecosystems?*

3. Research strategy

The research approach is essentially explorative with the aim of structuring and validating a business model design tool that integrates both *foresight* and *ecosystem logic*. Specifically, the approach is grounded on the key tenets of design science (Hevner et al., 2004; Hevner, 2007). Over the last twenty years, design science has gained relevance among management scholars to bridge the academia-practice gap by developing research knowledge in the form of solutions for managerial problems (Aguinis et al., 2014; Starkey et al., 2009; Van Aken et al., 2016). Importantly, these solutions do not target specific problems but classes of problems, extending descriptions, explanations and predictions conceived in academic settings and thus occupying a middle ground between theory and actual application (van Aken, 2004). In this sense, generalization occurs whenever a solution can be transferred to contexts other than the ones in which it has been tested (Van Aken et al., 2016). These approaches proved to be particularly suited for "wicked problems" that are ambiguous, arise in complex and poorly defined environments, and involve social interaction, as exemplified by the context of our study (e.g., Mathieson, 2007).

Most of the current methodological guidelines have originated in the Information Science field (e.g., Hevner et al., 2004; Peffers et al., 2007; Gregor & Hevner, 2013), the approach has extended across fields with minor adaptations (e.g., Battistella et al., 2013; Blanka et al., 2022; de Souza et al., 2019). Common elements are iterative cycles between the theoretical sphere and the problem space. The output of design science research is artifacts, broadly defined as constructs, models, methods, or instantiations (Hevner et al., 2004; Peffers et al., 2007). In management, artifacts encompass management systems, practices, tools, models, methods, conceptual frameworks and design principles addressing a real-world problem (Blanka et al., 2022).

Building on prior works, we followed the research process described in Fig. 1: framing, theorizing, creating, and validating. Both the problem definition and the proposed solution were theoretically grounded, whereas an exemplary empirical context provided a concrete view of both the challenges at hand and the potential of the proposed approach (Peffers et al., 2007). Three activities were performed: a structured literature review, a conceptualization of the *FEBM* design tool, and a single case study. The single case study design is appropriate for explorative investigations to demonstrate and validate the applicability of a method or solution to a given managerial issue (Hevner et al., 2004). The object of the case study was the test of the proposed *FEBM* design tool. These activities are described in greater detail in the following paragraphs.

3.1. Systematic literature review

The objective of the literature review was twofold: (1) identify and analyze prior literature on business model design, ecosystems, and foresight to inspire the design of FEBM; and (2) systematically assess studies on the implementation of green technologies to identify challenges and opportunities as well as industry-level evolutions and implications for the business models of individual firms. This second objective was important to understand the peculiarities related to business model design in a context of high uncertainty and interdependence (i.e., the sustainability transition).

The review followed the methodological guidelines of Tranfield et al. (2003) and Durach et al. (2017). Two researchers were independently involved. The articles have been selected using Elsevier Scopus database, one of the largest databases offering a comprehensive overview of research published in peer-reviewed outlets. We considered only articles published in English in journals in the area of Business, Management and Accounting. Two keyword searches were performed. For the literature on business model design against uncertainty and interdependence (1), methods and results have already been described in Section 2 (Literature background). As far as the implementation of technologies for sustainability transitions (2) is concerned, we included keywords that accounted for general terms (i.e., *clean tech**, *sustainability tech**, *green tech**) and specific recent applications (i.e., *renewable energy*, *carbon capture*, *hydrogen*, *alternative fuel*, *biofuel*). A total of 6698 documents was collected. We also examined relevant grey literature on the topic (e.g., white papers coming from the World Economic Forum, Word Energy Council, International Energy Agency, and leading management consulting firms). In terms of inclusion/exclusion criteria, these have been explicitly defined. We included papers that explained the business model design and ecosystem alignment structure and that more generally reported their implementation (e.g., addressing drivers, barriers, challenges, enablers, firm-, ecosystem-, and industry-level implications, contextual factors). We excluded articles aimed at proposing new technologies or assessing their environmental impact. The selection process consisted of reading the title and abstract first, then the full text. Further references were integrated through a backward/forward approach.

The final list of papers was composed of 156 papers. These were coded through an inductive-deductive approach. For (1), the categories referred to the aims (e.g., define a concept/tool, present a typology/taxonomy, analyze a case), the constructs used (e.g., business model, ecosystem, industry), the temporal perspective (e.g., past-, present-, or future-oriented), underpinning theory (if any), representation (e.g., graphical, flowcharts, narrative, tables), and dimensions (i.e., the elements used to describe, represent, and analyze the related constructs). The studies on (2) were coded based on antecedents (i.e., drivers and barriers), implementation patterns (i.e., challenges, enablers, interorganizational relationships), and contextual factors (i.e., country, industry).

3.2. Conceptualization of the business model design tool

Starting from the results of the literature review, the approach used to define the FEBM tool encompassed three phases aimed at defining the core dimensions and the "design nexus" among business models, ecosystems, and socio-technical scenarios (Pries-Heje & Baskerville, 2008).

First, based on the results of the literature review, we clustered the dimensions used to describe, represent, and analyze business models and ecosystems. These were included in analytical categories based on internal consistency and mutual exclusiveness, considering the interplay between the two levels of analysis. The process involved three researchers in multiple rounds of discussion.

As a second step, the foresight logic was addressed. Building on the literature on green technologies, a series of possible elements of uncertainty were identified. These elements could refer to the firm (e.g., the risks of managing innovation), the ecosystem (e.g., strategic choices of companies developing complementary technologies), and the broader socio-technical context (e.g., policy, technology, and regulation). Considering that firm- and ecosystem-level uncertainties were within the scope of ecosystem strategizing and subsequent business model design, we decided to formulate scenarios only for the socio-technical context (Nowack et al., 2011). The uncertainties were grouped into categories refining frameworks already proposed in the literature (e.g., Geels, 2010; Unruh, 2000; Rip & Kemp, 1998).

The third and last phase concerned the analysis of the relationship among the business model, the ecosystem, and the socio-technical context. Based on this, we defined the process steps of FEBM. To make it easily exploitable at an operational level, the key dimensions and subdimensions of each level of analysis were formulated in a tabular form. A modular logic was used for simplified compilation. Moreover, we defined a list of activities to be performed using the tool and related approaches (e.g., desk research, expert involvement, teamwork).

3.3. Case study

The last phase in a design science process consists of testing the artifact (Hevner et al., 2004; Peffers et al., 2007). Different approaches are possible depending on the contribution made by the study to both literature and practice (Gregor & Hevner, 2013). Observational validation of the artifact implementation appears particularly suited for managerial tools aimed at analysis and decision-making (e.g., Blanka et al., 2022; de Souza et al., 2019).

According to Yin (2003), case study research design is suitable for describing an intervention and its context. In this study, the intervention refers to the application of the proposed artifact (FEBM), while the context is the e-fuel ecosystem under investigation. Like many ecosystem studies (e.g., Adner and Kapoor, 2010), we chose a case where a loosely connected group of actors is engaged in developing new technologies and innovations.

The test of the *FEBM* involved two key steps. First, the research team examined relevant project materials, performed multiple rounds of interviews with project members, and carried out additional desk research on relevant material, including regulation, analyst reports, market research, company profiles, white papers, and technical reports. The analysis led to a provisional processing of the materials into the tool. Based on this, the tables were modified by adding or editing some dimensions and subdimensions related to each level of analysis (i.e., business model, ecosystem, socio-technical context). The second phase envisioned the engagement with project members through one-to-one interactions, a questionnaire, and an online half-day workshop augmented by the use of web-based tools. The workshop involved 16 representatives of the organizations involved in the eForFuel project and three external advisors. The feedback on the use of the tool was overall positive and their suggestions were incorporated to fine-tune the *FEBM* approach.

3.3.1. Industry selection

The industry was selected in that it exemplified the challenges related to business model design in contexts characterized by uncertainty and ecosystem-level interdependencies. These industries are indeed the most impacted by disruptive technological changes (Huijben et al., 2016; Hess, 2014). In this respect, the shift of the energy system from fossil sources appears crucial. Efuels are an emerging class of synthetic fuels that are manufactured using carbon dioxide (CO_2), electricity (ideally obtained from renewable sources), and water. The CO_2 to be used as a feedstock should come from carbon capture, either from an industrial point source (e.g., steel and cement plants, which are the industries with the highest emissions) or from direct air capture. Engineered microorganisms are used in the process to yield industrially relevant products. Efuels represent an alternative to conventional fossil fuels and biofuels based on agricultural production. They can be marketed for transport and heating purposes with a significant reduction in overall emissions due to CO_2 circularity (the CO_2 that is released in the air as the fuel is burnt comes from carbon capture).

This empirical context is appropriate to apply and test the *FEBM* design tool because:

- Technologies in the field are rapidly reaching maturity, prompting firms to reflect more concretely on commercialization and related value-creation opportunities.
- There is a high level of uncertainty in several aspects of the socio-technical context. These refer, for example, to the maturity and cost-effectiveness of complementary technologies (e.g., those for carbon capture usage and storage) and competing ones (e.g., alternative sources of energy such as hydrogen and electric power), the direction and strength of policy initiatives, and social acceptance (Ueckerdt et al., 2021; Chiaramonti et al., 2021).
- The production and commercialization of efuels are subject to significant interdependencies among firms operating across different

industries (e.g., industrial players, fuel producers and distributors, technology providers, and transport companies) (Lindstad et al., 2021; Tsvetkova & Gustafsson 2012). These players thus need to adapt their processes and business models.

Firms that develop or plan to adopt efuel technologies should start as early as possible to explore possible business model configurations while systematically addressing ongoing uncertainties (i.e., *foresight logic*) and concurrently aligning their approach based on interdependent evolutions of other firms (i.e., *ecosystem logic*).

3.3.2. Case selection

The case study is the eForFuel project, a research project that was funded under the eight European Framework Program for Research and Technological Development (Horizon 2020). The purpose of the project was to develop an industrial biotechnology solution using electricity and microorganisms to convert CO_2 into fuels, thus providing a sustainable replacement of fossil carbons. The activities addressed methods for metabolic conversion of electrochemically produced formate.

The case represented the ideal setting to apply the FEBM design tool for several reasons, including a fit with our endeavor (i.e., theoretical sampling) and the opportunity to engage with project participants to design their business models. First, the technologies focused on the project had an intermediate level of maturity, so that assumptions regarding process flows and efficiency could be made. Second, the project involved actors that were positioned differently within the emerging efuel ecosystem (i.e., industrial players, research institutes, technology developers, technology providers, fuel producers, and distributors). Although the interests of these players overlapped, each of them also had its own agenda, so the definition of an alignment structure was needed. Third, the boundaries of the ecosystem were yet to be defined, as the successful commercialization of underlying technologies hung on the engagement of firms that were not yet involved in the project (e.g., industry incumbents, technology complementors). Finally, the project coordinator had already performed several analyses, was willing to engage in business discussions, and was eager to onboard the other partners and external consultants. This granted an environment in which we could productively interact and collaborate to conceive and refine the proposed tool.

4. The future ecosystem business model (FEBM) tool

This section presents the proposal for a business model design tool that integrates both a *foresight* and an *ecosystem* logic to be used in support of managerial decision-making in contexts characterized by both uncertainty and interdependencies.

The tables, activities, and suggested analytical approaches enable the systematic simplification and progressive integration of the key elements that determine ecosystem strategizing and a consistent definition of business model options for individual firms. The *FEBM* consists of three building blocks. The first one (*1. Developing socio-technical scenarios*) is a foresight exercise aimed at identifying the key elements of uncertainty affecting the introduction of the proposed innovation/technology. These elements are related to the broader business environment, the scientific and technological landscape, policy and regulatory aspects, and the cultural and societal context. The second block (*2. Defining ecosystem configurations*) addresses the interdependencies among the business models of the different firms that are involved in or impacted by the proposed innovation/technology. For each scenario detailed in the first phase, the tool enables managers to “play the ecosystem game” while aligning their expectations with those of key partners. Finally, the third building block (*3. Designing integrated business models for the firms within the ecosystem*) is about the formulation of a parsimonious set of business model options for each firm within the ecosystem.

Fig. 2 synthesizes the main elements of the *FEBM* design tool. For each building block, Table 2 provides a high-level description, the list of activities, some suggested approaches, and the expected output, which are described in the following sections.

4.1. Developing socio-technical scenarios

The objective is to define the key characteristics of the socio-technical context to define opportunities and constraints (Wesseling et al., 2020). In this respect, the approach builds on the concept of socio-technical scenarios, which are qualitative storylines of possible futures that can be complemented with quantitative projections. Socio-technical scenarios are a common foresight approach for major innovations, as those related to emerging paradigms in the energy sector (e.g., Hofman & Elzen, 2010; Verbong & Geels, 2010). They encompass techno-economic aspects as well as social acceptance, institutional change and political feasibility (Geels et al., 2020; Elzen et al., 2004; Hofman et al., 2004; Hofman & Elzen, 2010).

The first step is a structured scoping activity (*1.1. Identify the scope of the proposed innovation/technology*). The features and development timeline of the proposed technology/innovation should be reviewed, and its main outlet markets identified. It is also important to assess what technologies, products, or services will be substituted following its introduction. In the case of a technology to be used in industrial processes, the main process steps, upstream and downstream activities should be outlined. For scoping purposes, it is usually sufficient to examine internal material (e.g., project presentations, memos, descriptions), to interview the researchers and managers directly involved in the project, and to review publicly available information (e.g., industry reports). Should the scope of the proposed innovation/technology still not be clear at this stage, it is also possible to analyze patent data (e.g., Lee et al., 2018; Joung & Kim, 2017; Kim & Bae, 2017). The expected output is a workbook containing all the relevant information (***1A. Innovation/Technology workbook***). It includes the technical characteristics and development roadmap of the proposed innovation/technology, related technologies and infrastructures, as well as the explication of the main application areas and markets.

Starting from here, the second step aims to clarify the relevant factors for the development of socio-technical scenarios (*1.2. Collect and analyze information for socio-technical scenario development*). These factors refer to four main dimensions, which, building on the MLP, have been adapted from the work of Wesseling et al. (2020) and Huijben et al. (2016). The dimensions are:

- *1.2.1. Business environment*: Various constructs and analytical frameworks are normally used to make sense of the network of competitive, cooperative, and transactional relationships around firms. These include market and industry (e.g., Amit & Schoemaker, 1993; Schmalensee, 1985; Porter, 1980), value chain, value network, and value system (e.g., Gibbon et al., 2008; Stabell and Fjeldstad, 1998), and ecosystem analysis (e.g., Jacobides et al., 2018; Adner, 2017). A syncretic approach is needed to map the characteristics and trends affecting the outlet markets, the competitive landscape, upstream, downstream, and adjacent sectors that offer complementary products and services. The data collection and analysis should thus include the following dimensions: players' fragmentation/consolidation, vertical integration/specialization, dynamism, barriers to entry, growth, and marginality.
- *1.2.2. Science and technology*: The analysis should address both competing technologies (i.e., “old” technologies/products/services which will be substituted and alternative “new” ones – Utterback & Suárez, 1993; Dosi, 1982) and complementary technologies, infrastructures, and resources (i.e., those that need to be utilized in conjunction with the proposed innovation/technology; Teece, 2006; Teece, 1986). The analysis should uncover benefits and constraints, technological roadmaps, likelihood of success, expected costs, and the main players involved.

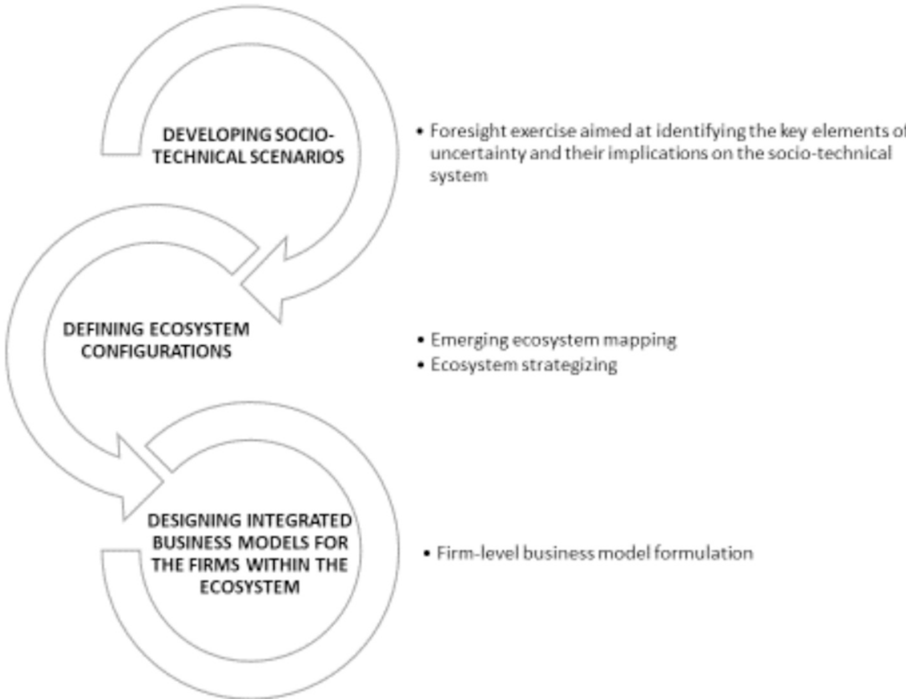

Fig. 2. Building blocks of the FEBM.

- *1.2.3. Policy and regulation*: The review should clarify the goals and timeline of policy initiatives affecting the development and adoption of the proposed innovation/technology as well as those related to competing and complementary solutions. It is important to understand the overarching characteristics of the policy mix (e.g., sustaining the development of alternative technologies or weakening the position of incumbent solutions and players) and identify the most relevant policy instruments. Frameworks and classification approaches can be found in the recent literature, such as in Kanger et al. (2020) and Rogge & Reichardt (2016).
- *1.2.4. Culture and society*: Different aspects need to be assessed, including demographic evolutions and potential shifts in dominant cultural paradigms. These aspects might influence not only the acceptance and diffusion of the proposed innovation/technology (Peres et al., 2010; Venkatesh et al., 2003) but also future policy-making and the strategies pursued by other firms in the industry (Battistella & De Toni, 2011). It is important to consider both long-lasting trends (e.g., climate change, sustainability; Mittelstaedt et al., 2014) and the impact of sudden, unexpected events (e.g., wars and international crises; Sheth, 2020; He & Harris, 2020).

Relevant information alongside these dimensions is usually found through desk research by screening previous academic literature, policy documents and white papers, reports of industry associations, consulting firms, and international organizations, market research, business press articles, annual reports and presentations of the main players involved in technology development and in the broader business environment. These sources can be complemented through the engagement of topic experts in interviews or surveys. The material should be stored in a shared folder (***1B. Socio-technical information folder***).

The analysis should simplify the possible characteristics of the future context. To this end, for each dimension a set of projections (i.e., short future theses) should be formulated, the reference year being the one when the proposed innovation/technology will be market-ready (it is recommendable not to go beyond a 10–15-year horizon; Nowack et al., 2011). The projections should be short, cover one concept at a time, and avoid ambiguities and conditional sentences (for guidelines see Rowe & Wright, 2011; Loveridge, 2002; Mitchell, 1991). Should there be uncertainty regarding a specific future thesis, it is anyway advisable to formulate a hypothesis. The projections can be accompanied by a level of confidence (e.g., whether the examined information presented elements of uncertainty or contradictions). The outcome is a file containing the full list of projections (***1C. List of socio-technical projections***).

The last step consists of the formulation of a series of different narratives of the future (*1.3. Develop socio-technical scenarios for the reference year*). Scenarios are built following likelihood and consistency analysis (Culot et al., 2020; Johansen, 2018; Lehr et al., 2017). The projections are first assessed for their likelihood and potential impact on the proposed innovation/technology. Once the baseline scenario (i.e., the one that seems more likely) is formulated, the projections characterized by high uncertainty/impact are used to describe alternative futures. To this end, starting from the list and preliminary analysis included in 1C, it is important to involve project members and external industry experts through workshops, interviews, or a multiple round Delphi-based scenario analysis (Nowack et al., 2011; van Notten et al., 2003). For the sake of simplicity, it is advisable to conceive four to six different scenarios, which may be further detailed according to some variations. The descriptions should be included in a report (***1D. Socio-technical scenarios***).

4.2. Defining ecosystem configurations

Here, the focus is on the interdependencies across the various activities and firms that are involved in or will be impacted by the introduction of the proposed innovation/technology. These interdependencies are first analyzed, and then possible ecosystem configurations are posited. The first step is thus about mapping the relevant activities and actors, namely the firms potentially involved in the ecosystem (*2.1. Analyze the structure of the ecosystem*). Information for this can be derived from the previous phase (see 1.2.1 Business environment). An adjacency matrix (nxn) can be used to assess the possible attribution of activities (columns) to actors (rows). In the area of the matrix, each row-column intersection is rated according to the following criteria: “3” – already part of current actors' core competences; “2” –

Table 2
Outline of FEBM activities, approaches, and output.

FEBM building blocks and description	Activities	Suggested approach(es)	Output	Main references
1. Developing socio-technical scenarios				
The characteristics of the socio-technical regime are analyzed to identify the more likely future trends and key factors of uncertainty. Based on this, the baseline scenario and a set of alternative scenarios are developed and outlined.	1.1. Identify the scope of the proposed innovation/technology by focusing on: 1.1.1. The main outlet market(s) (i.e., products/services to be delivered, technologies/products/services to be substituted, perspective customers/ markets); 1.1.2. The key process steps, including upstream and downstream activities (in case of a technology to be used in industrial processes); and 1.1.3. The development timeline.	- Desk research and analysis of relevant internal materials (e.g., project presentations, technical descriptions); - One-to-one interviews with key project members, including researchers, scientists, managers; and - Desk research and analysis of similar innovations/ technologies (e.g., performing a patent analysis, analyzing industry reports).	***1A. Innovation/ Technology workbook***	Voelpel et al., 2005; Weigand et al., 2007; Ries, 2011; Maurya, 2010; Furseth and Cuthbertson, 2013
	1.2. Collect and analyze information for the development of socio-technical scenarios. The following dimensions are considered: 1.2.1. Business environment (outlet markets, competitive landscape, upstream, downstream, and adjacent sectors): players' fragmentation/ consolidation, vertical integration/ specialization, dynamism and barriers to entry, growth, and marginality; 1.2.2. Science and technology (competing and complementary technologies/infrastructures): technological roadmaps, likelihood of success, expected costs, benefits and constraints, players involved; 1.2.3. Policy and regulation (affecting the proposed innovation/technology as well as competing and complementary innovations/technologies): characteristics of the policy mix, identification of specific policy instruments; and 1.2.4. Culture and society: preferences, biases and stigmas, habits, demographics.	- Desk research and analysis of relevant materials (e.g., academic literature, policy documents and white papers, reports of industry associations, consulting firms, and international organizations, market research, business press articles, annual reports, and company presentations); - Expert study (e.g., one-to-one or group interviews, survey, other forms of engagement).	***1B. Socio-technical information folder*** ***1C. List of socio-technical projections (i.e., future state statements)***	Seelos & Mair, 2007; Furseth and Cuthbertson, 2013; Remane et al., 2017; FW, 2023
	1.3. Develop socio-technical scenarios by: 1.3.1. Formulating the description of the baseline scenario; 1.3.2. Detailing a parsimonious set of alternative scenarios; 1.3.3. Developing quantitative models (whenever a reliable market sizing is not already available).	- Group interaction with key project members and external industry experts (e.g., workshops, Delphi study); and - Development/refinement of quantitative projections.	***1D. Socio-technical scenarios***	Battistella et al. 2013; Fritscher and Pigneur, 2014; Remane et al., 2017; Coffay & Bocken, 2023
2. Defining ecosystem configurations				
Considering the baseline scenario, the focal value proposition of the ecosystem is formulated. The activities are attributed to the various players within the ecosystem and partnerships/ alliances are posited. Potential variations depending on alternative socio-technical scenarios are defined.	2.1. Analyze the structure of the ecosystem by: 2.1.1. Identifying the set of interdependent activities and actors involved (i.e., firms); and 2.1.2. Assessing plausible attributions of activities to the actors within the ecosystem.	- Desk analysis and validation with key project members.	***2A. Configuration matrix***	Gordijn, 2004; Battistella et al. 2013; Hamwi et al., 2021; Circit nord, 2023; Brea, 2023
	2.2. Formulate the focal value proposition of the proposed innovation/ technology by: 2.2.1. Detailing possible value propositions for the baseline socio-technical scenario and alternative ones; and 2.2.2. Analyzing commonalities and differences.	- Group interaction with key project members (e.g., workshop, focus group, Nominal Group Technique).	***2B. Scenario-dependent focal value propositions***	Allee, 2000; Hamwi et al., 2021; Circit nord, 2023
	2.3. Define ecosystem configurations to deliver scenario-dependent focal value propositions by: 2.3.1. Formulating configuration hypothesis for each value proposition (i.	- Group interaction with key project members (e.g., workshop, focus group, Nominal Group Technique); and - Desk analysis and validation with key project members/ industry experts.	***2C. Ecosystem structure flowcharts and comments***	Marin et al. 2007; Tian et al. 2008; Goethals, 2009; Battistella et al. 2013; Faber et al., 2018b

(*continued on next page*)

Table 2 (*continued*)

FEBM building blocks and description	Activities	Suggested approach(es)	Output	Main references
	e., actors, activities, positions, and links); 2.3.2. Assessing advantages/ disadvantages and fit with current/ foreseen business models of key players; and 2.3.3. Analyzing commonalities and differences.			
3. Designing integrated business models for the firms within the ecosystem				
Firm-level business models are conceived for each ecosystem configuration (i.e., scenario-dependent focal value proposition and structure).	3.1. Define firm-level business model options by: 3.1.1. Designing firm-level business models based on the different ecosystem configurations; and 3.1.2. Analyzing commonalities and differences to distill main features and potential variations.	- Desk analysis and validation with key project members.	***3A. Business model playbook***	Joyce and Paquin, 2016; Kamoun, 2008; Hulme, 2010; Osterwalder & Pigneur, 2010; Maurya, 2010

very likely extensions of actors' core competencies; “1” – not likely to be part of actors' core competencies, but possible under specific circumstances; “0” – not feasible or extremely unlikely. The output (***2A. Configuration matrix***) should be validated by key project members.

The next step concerns the construction of the focal value proposition in light of the characteristics of the socio-technical scenarios (*2.2. Formulate the focal value proposition of the proposed innovation/technology*). The value proposition describes the comprehensive value/benefit that the firms involved in the ecosystem can create and not what any individual firm is to deliver (Adner, 2016; Chesbrough & Rosenbloom, 2002). In this step, key project members should be involved through informal workshops or more structured interaction techniques such as focus groups or Nominal Group Technique (Boddy, 2012; Bartunek & Murninghan, 1984). Commonalities and differences among the value propositions formulated for the different scenarios should be assessed and summarized (***2B. Scenario-dependent focal value propositions***).

As a last step, an analysis of the ecosystem structures is performed to better deliver the various scenario-dependent focal value propositions. In line with Tsvetkova & Gustafsson (2012) and building on the concept of modularity (Schilling & Steensma, 2001; Schilling, 2000), the configuration matrix (2 A) is used to identify possible options. This leads to the definition of the positions of activities/actors within the ecosystem according to both the input-output flow and technological constraints. The links among actors are specified (e.g., supply agreement, service provision, partnership, or alliance). The advantages and disadvantages of each possible configuration should be discussed with the key project members and industry experts. A further check on the fit of the proposed configuration with the current business model and the stated strategy of the main players in the ecosystem is also appropriate. Finally, it is important to analyze the commonalities and differences among the different configurations and to clearly explicate the underpinning factors. The output (***2C. Ecosystem structure flowcharts and comments***) provides a flowchart representation of each configuration and some notes on the socio-technical scenario(s) of application, the focal value proposition, advantages, disadvantages, and caveats.

4.3. Designing integrated business models for the firms within the ecosystem

The outcomes of the previous activities are used to design firm-level business models that account for scenario-dependent ecosystem configurations. The activity should aim at defining a set of options (*3.1. Define firm-level business model options*).

Different frameworks and dimensions have been put forward by previous research on business models (e.g., Teece, 2018; Osterwalder & Pigneur, 2010; Osterwalder et al., 2005; Chesbrough & Rosenbloom, 2002; Amit & Zott, 2001). The deliverable (***3A. Business model playbook***) should contain an outline of the business model for the baseline scenario as well as possible variations depending on alternative socio-technical scenarios and ecosystem structures. This exercise can be done by kind of actors (e.g., “producers”, “retailers”) or for specific players that are involved in the development of the proposed innovation/technology.

5. Application of the FEBM tool to the case study

The application of the tool is illustrated in Appendix outlining how the analytical and decision-making process was applied as well as the results obtained. Tables and figures are included for illustrative purposes, any information or detail posing privacy or confidentiality risks has been removed.

6. Discussion and implications

This study presents a new business model design tool (FEBM) integrating both a *foresight* and an *ecosystem* logic. The tool was developed through a design science approach (Hevner et al., 2004; Peffers et al., 2007). The need for such a tool was motivated by the fact that, although there is growing awareness about the relevance of organizational agency in sustainability transitions (Geels, 2020; Wesseling et al., 2020), there is a dearth of frameworks and practical approaches supporting managerial decision making in this respect. Instead, as companies are venturing into far-reaching systemic changes needed to address the environmental crisis (Andersen & Markard, 2020; Markard et al., 2012), theory-grounded field-tested approaches can guide managers towards a deeper understanding of options and related risks. The FEBM was built on the theoretical backbone of the MLP and leveraged various streams of literature that have only a partial overlap. The problem context is indeed required to consider a design nexus among these streams (Pries-Heje & Baskerville, 2008). This entailed several complexities related to the conceptualization and description of the interdependencies between and within levels of analysis.

The field test in the efuel industry showed that integrating different perspectives early on can indeed support firms in understanding where to focus their future business, what key relationship to pursue, and what contextual factors to consider. This is often a neglected aspect against major technological challenges that need to be addressed. However, a better understanding of future business options is key to orient discussion among project partners (including non-economic actors, such as universities and research institutes) and for framing relationships in a rapidly evolving context. For example, by applying the FEBM tool, we were able to highlight that—across various scenarios—there was a strong need to find alignment with carbon capture technology providers who were not part of the eForFuel project partnership. Similarly, it emerged clearly that Oil&Gas incumbents, while shifting from fossil sources, needed to be taken into consideration as a key node. Following this logic, the managers involved in the field test considered as the first option to apply eForFuel technologies industrial parks, as players from different industries (including plants generating CO_2) are already colocated. The case evidence suggests that starting from the application of the FEBM to systematize and simplify uncertainties and interdependencies, managerial discussions can take place that further detail the implications of each scenario-dependent ecosystem configuration both at inter-organizational level and considering individual firms' business models. These considerations—informed by the feedback we received from the managers during and after the field test—constitute the validation of the proposed tool (Peffers et al., 2007).

The originality of the FEBM lies in integrating an ecosystem and a foresight logic into business model design, addressing existing shortcomings in two main areas: ecosystem strategizing and future-oriented exploration. Unlike current tools, the FEBM enables effective generation and evaluation of alternative scenarios in the early stages of business model design. Moreover, in contrast to current approaches for mapping interactions between firms, the FEBM allows to frame the interplay between firm-specific choices and ecosystem alignment structures, recognizing the active role that firms can play and enabling joint assessment of strategic options (e.g., Kanda et al., 2021; Wesseling et al., 2020). While existing tools focus on these aspects separately, our approach integrates them for a more comprehensive understanding of the complexities involved in shaping successful business models within dynamic and uncertain environments. From a theoretical standpoint, by bridging different levels of analysis (i.e., business model, ecosystem, socio-technical context), our effort captures the growing attention towards the multi-level implications of systemic changes such as those implied by sustainability transitions (Liu et al., 2021; Bögel et al., 2019; De Haan & Rotmans, 2018). Moreover, our field test addressed current gaps in research on business model exploration tools in terms of projects in which researchers, managers, and consultants collaborate (Athanasopoulou and De Reuver, 2020).

6.1. Implications for theory

The development of the FEBM tool contributes to the literature in at least three ways. First, in light of a growing interest in sustainability transitions, scholars have argued for a better understanding of individual firms' role and scope of action against far-reaching changes and ongoing uncertainties (Bögel et al. 2019; De Haan and Rotmans, 2018). Through the field test on the eForFuel case, we were able to leverage previous conceptualizations of the socio-technical contexts and elaborate them into a practical analytical framework that can be used for firm-level business model analysis. Namely, we built on the latest theoretical advancements of the MLP (e.g., Wesseling et al., 2020; Walrave et al., 2018) to build a new tool that integrates concepts from various research traditions. Second, our effort answers recent calls for tools supporting the exploratory phases in which new business models are conceived (Athanasopoulou and De Reuver, 2020). In this respect, the FEBM tool allows the generation of alternative business models depending on the socio-technical scenarios (*foresight logic*) and the interdependencies with other firms (*ecosystem logic*). Third, while the literature has amply argued for ecosystem strategizing (Adner, 2017; Shipilov and Gawer, 2020), there is still a lack of practical approaches, especially considering that research generally assumes a central role of a lead firm in shaping the ecosystem rather than alignment structures among firms (Brink, 2023). The proposed approach and the field test show how firms can explore strategic options for ecosystem design together, considering their business models and the implications for their business partners.

Overall, our effort aligns with growing calls for impact across managerial disciplines. This work follows on concerns of a limited application of scientific knowledge to real-world problems so that non-explicatory paradigms—design science among them—have been hailed as potential bridges between theory and practice (Aguinis et al., 2014; Starkey et al., 2009). In this respect, the implications emanating from our work are meta-theoretical in that a methodology which can be applied to a class of managerial problems is proposed (van Aken, 2004).

6.2. Implications for practice

This study has major implications for practice. With respect to business leaders and innovation managers, the FEBM tool provides a practical analytical approach for exploring alternative business models based on the most relevant context uncertainties and inter-organizational interdependencies. The FEBM tool spells out the relevant dimensions and questions to systematically incorporate these aspects into firm-level choices while outlining the key process steps, activities, and outputs (Table 2). The field test provides a concrete example of the application of the tool, which presents several elements of novelty against current approaches (Table 1). Moreover, the tool can be used to structure discussions with current and prospective business partners by focusing managerial attention on the key elements and options. Overall, the FEBM translates recent MLP theoretical into a practical method by integrating them into concepts that are familiar to the managerial community.

Our experience in the application of the tool suggests three ground rules for practitioners. First, the approach can be successful only by engaging both key project members and external industry experts. Not only is stakeholders' buy-in essential to any future action based on the outcomes of the analysis, but the reliability of the results also depends on the extent to which different (and unbiased) points of view can be considered. Second, the application should aim at the identification of a few alternatives based on opposing assumptions (Output 1D). A complete and detailed outline of the possible effects of any external contingency would, in fact, derail managerial attention. Third, we realized that a more open discussion among project members could be facilitated by abstracting the discussion from the actual firms involved in the partnership to generic "actors". In this respect, the flowcharts (Output 2C) and the business model playbook (Output 3 A) should not contain explicit references to project members.

Other implications concern policy-makers. We tested the methodology on a European-funded project on technologies with an intermediate level of maturity. The dialogue with the project coordinator and further exchanges with other project members indicated that there are significant challenges in identifying and discussing actual business model options supporting such ventures. Systemic changes—the sustainability transition is a case in point—demand both a *foresight logic* and an *ecosystem logic* in business model formulation that is normally not included in current approaches. Given the increasing attention on ensuring the impact of funding, the FEBM tool puts forward a framework that accounts for these aspects and that can serve as a basis for institutional discussions.

7. Conclusions

Increasingly, firms operate in a context characterized by far-reaching systemic changes that are still clouded by significant uncertainty. A case in point is sustainability transitions. The urgency to address climate change is prompting policy action, technology development, and new operating models that span from energy generation to product manufacturing and the demand side. The breadth and depth of interdependencies require not only theoretical elaboration but also practical approaches to support key actors in navigating complexity and uncertainty that unfold at multiple levels (Liu et al., 2021; Geels et al., 2020; Wesseling et al., 2020). Firms investing in innovation within a paradigm shift need not only to anticipate future trends but also to understand implications that relate to their own business and the network of inter-organizational relationships they can structure. The FEBM tool provides a compelling approach to help managerial decision-making on alignment structures. Under this premise, it is still important to outline existing limitations which can be addressed by future research.

7.1. Limitations and future research directions

It is important to note that the test is context-specific to the case study, which means its effectiveness has been demonstrated in that particular scenario. However, the theme of the test is the method itself, not a specific forecast of the industry. This implies that the tool could be applicable in other contexts as well, but careful consideration of contextual factors that may influence its effectiveness is necessary. The proposed tool is generic, suggesting its potential adaptability to different contexts, although some minimal adjustments may be required to make it effective in different settings. Consistent with design science principles (Gregor & Hevner, 2013), the FEBM tool was built to be applied across various situations requiring business model exploration in contexts characterized by high uncertainty and ecosystem-level interdependencies. With this aim, its building blocks and related activities (Table 2) are meant to address common and general aspects, which might be further detailed to account for some specificities related to the technology, the industry, and the players involved. Further research could, therefore, test the approach in other empirical settings, thus providing further details and broader validation.

The development of a tool typically undergoes a first stage of "a-testing" (i.e., proving the efficacy in one specific problem context) and subsequent phases of "b-testing" as the tool is applied in other contexts where third parties use it, assess its usefulness, and make final enhancements (van Aken, 2004). Among the key contextual factors that can influence the applicability and effectiveness of the tool are industry dynamics, organizational characteristics, and regulatory environments. Industries can vary significantly in their operations, objectives, and business practices, which may require modifications to the tool to make it effective in different contexts. Organizational characteristics such as size, structure, and culture can also influence the ability to adopt and use the tool effectively. Additionally, regulatory environments can vary greatly from one country to another and can have a significant impact on the implementation and effectiveness of the tool. An important aspect to consider is the strength and degrees of freedom in influencing partners within the ecosystem. In some cases, there may be partners or stakeholders who have a significant influence on decision-making processes and who may be more or less inclined to adopt the proposed tool and implement the managerial consequences. The ability to influence these actors and gain their involvement can be crucial to the success of the tool. Addressing these challenges may require careful evaluation and possible adjustments to the tool to ensure its success in various contexts.

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CRediT authorship contribution statement

Giovanna Culot: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Conceptualization. **Cinzia Battistella:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Data availability

Data will be made available on request.

Appendix A. APPENDIX - Application of the FEBM tool to the case study

A.1. Developing socio-technical scenarios for efuel technologies

A.1.1. Identify the scope of eForFuel technologies

The first step consisted in a set of interviews with various individuals employed at the project coordinator and the review of relevant material (e.g., internal presentations, project deliverables). A patent analysis was already performed to identify possible outlet markets.

These activities led to the definition of the scope of the proposed technologies in terms of products (formate and different efuel types), applications (efuels for different types of transports and material production), substitutions of existing products, and key process steps. Upstream, the process required the supply of CO_2, renewable energy, and water; formic acid represented an intermediate output (the process required in fact a mediator between the electrochemical process and the bioreactor). Downstream, depending on the specific fuel to be produced, alternative routes included oligomerization, hydrogenation, and compression. The level of maturity of the technology was intermediate, requiring further testing and refinements. Should the development proceed as planned, the technology was expected to be market-ready by 2030.

The Table A.1 - *Output 1A. Innovation/technology workbook* was structured in the form of a spreadsheet. The agreed-upon role of each project partner with respect to research, production, and commercialization of the products/intermediate products was also reviewed. The innovation/technology workbook was organized as a matrix. Columns represents different efuels. In rows, we included applications and key process steps. Confidential information on the role of project partners was removed.

Table A.1
Output 1A. Innovation/technology workbook (simplified).

		Products				
Applications		Formic acid	Isooctane	Isododecane	Propane	Isobutene
Transport	Fuel	–	Substitution: replace gasoline	Substitution: replace gasoline replace jet fuel (including bio/ renewable jet fuels)	Substitution: replace jet fuel (including bio/ renewable jet fuels) replace LPG (including bio LPG)	Substitution: replace jet fuel (including bio/ renewable jet fuels)
	Additive	–	Substitution: replace ethanol as additive New applications: enhance ethanol performance	New applications: enhance ethanol performance	New applications: enhance biogases' performance	Existing applications: enhance gasoline performance
Heating		–	–	–	Substitution: natural gas	
Materials and other applications (after further processing)		Existing applications: Plastics Pharma Food Leather tanning Glass silage Anti-icing Substitution: Corrosive mineral acids New applications: Fuel cells	–	–	Substitution: Petrochemical products (ethylene, propylene)	Substitution: Butyl rubber Plastic Lubricants Organic glass Chemicals Cosmetics
Process steps						
Upstream		Main inputs: CO_2 (from carbon capture) Renewable energy Water	Main inputs: Formic acid O_2			
eFF technologies		Electrolyzer	Bioreactor and microbials			
Downstream			Oligomeriza-tion Hydrogenation	Hydrogenation	Compression	

A.1.2. Collect and analyze information for socio-technical scenario development

Based on the outcomes of the first step, the material collection included the following item categories:

- *Business environment*:
  - Market research and academic articles on e-fuels, biofuels, and alternative fuels in general, maritime, road and air transport.
  - Annual reports and press releases of major Oil&Gas companies, biofuels and alternative fuel producers/distributors, (air, maritime, road) shipping companies, passenger transport companies, vehicle, ships, and aircraft manufacturers.
- *Science and technology*:
  - Market research, international reports, and academic articles on complementary technologies, namely Carbon Capture Utilization and Storage (CCUS) technologies, Genetically Modified Microorganism (GMM), bioreactors.
  - Market research, international reports, and academic articles on competing technologies. Here we considered both alternative engines (electricity and hydrogen-powered solutions) and other technologies for the production of e-fuels and biofuels (e.g., lignocellulosic, anaerobic digestion, hydrotreatment, algae, conversion of cellulosic and organic waste).
- *Policy and regulation:* European and US policies, regulations, and scenarios for renewable energy, efuels, and biofuels, transport decarbonization.
- *Culture and society*: academic articles, international reports, press articles on perception and acceptance of efuels and biofuels, electricity, hydrogen, CCUS, and GMM.

The material was stored in output *1B. Socio-technical information folder*. The information contained in each document was coded into an excel spreadsheet and clustered by similarity into socio-technical projections describing the future in a 10-year timeframe - *Output 1C. List of socio-technical projections*. The outcomes of the analysis are presented in Table A.2 To draw the attention on the most important elements, the research team together with the project coordinator analyzed each projection for the level of uncertainty (i.e., whether there was agreement in the sources) and its potential impact on the success of eForFuel.

Table A.2
Output 1C. List of socio-technical projections.

Analytical dimensions and subdimensions		Socio-technical projections: Future state	Uncertainty	Impact for eForFuel
1. Business environment	Outlet market(s)	The global market of formic acid has grown by over 50 %.	LOW	+
		Formate (i.e., the conjugate base of formic acid) is used as an energy carrier based on CO_2 storage.	MEDIUM	+ +
		Efuels are used in air transport.	MEDIUM	+
		Efuels are used in maritime transport.	MEDIUM	+
		Efuels are not used to power cars and small commercial vehicles.	LOW	- -
		Efuels are used to power heavy-duty vehicles.	MEDIUM	+ +
	Competitive landscape	Fuels and gases from traditional fossil sources have lower prices than those produced through alternative climate-neutral processes.	LOW	- -
		The production, storage, and distribution of formic acid/formate involves a small number of global players.	LOW	–
		Current players in the Oil&Gas sector have reconverted their production to alternative fuels (e.g., biofuels, efuels).	LOW	+ +
		Current players in the Oil&Gas sector have acquired relevant technologies to develop alternative fuels.	LOW	+
		Current players in the biofuel sector (crop-based) have not reconverted their production to efuels.	MEDIUM	–
		New players have entered the market to produce efuels.	MEDIUM	+
		The production of efuels involves a limited number of players.	MEDIUM	+
		The production of substitutes of fossil fuels and natural gases occurs on a regional basis.	LOW	+
	Upstream industries	CCSU from IPSs is deployed at scale in hard-to-abate industries (e.g., steel and cement).	MEDIUM	+ +
		CCSU from DAC is deployed at scale.	HIGH	+ +
		Captured CO_2 is mostly sold for/used in the production of efuels.	MEDIUM	+ +
		CCSU operations and subsequent CO_2 handling are performed by specialists (i.e., gas distributors, chemical companies, energy infrastructure companies, and digital platforms).	MEDIUM	–
		Hard-to-abate industries have adopted new technologies/products to reduce CO_2 emissions in the process (e.g., production routes based on directly reduced iron/scraps, storage of CO_2 in new concrete products).	MEDIUM	- -
		Renewable energy is not available at scale for industrial processes.	MEDIUM	- -
		Water is available at scale for industrial processes.	LOW	+ +
	Downstream industries	The distribution of efuels involves current players in the industry.	LOW	+
		The distribution of efuels involves a limited number of players.	LOW	+
		Air/maritime transport companies have set up partnerships locking in their efuel provision.	LOW	–
		There is a high number of small players involved in fuel transportation, storage, and blending.	LOW	+
	Adjacent sectors	There are several specialized CCSU technology providers.	LOW	–
		Several companies are active in the development and sales of engineered microbials for industrial processes.	LOW	+
2. Science and technology	Competing technologies	Most competing technologies for producing efuels are not ready to be adopted in the industry.	HIGH	+ +
		Technologies for producing efuels that have reached maturity are still not cost efficient.	MEDIUM	+
		Hydrogen technologies (green hydrogen) have reached maturity.	LOW	- -
		The infrastructure required to deploy hydrogen at scale have been completed.	HIGH	- -
		Electricity is not applicable to heavy-duty vehicles, maritime, and air transport due to inadequate power.	LOW	+ +
	Complementary technologies and infrastructures	IPS CCSU technologies have reached maturity.	LOW	+ +
		DAC CCSU technologies have reached maturity.	HIGH	+ +
		Infrastructures to store and transport CO_2 have been built at scale.	HIGH	+ +
		Gas grids have been adapted for new kinds of gases.	LOW	+ +
3. Policy and regulation	Affecting efuels	Life-cycle analysis frameworks attribute CO_2 released after efuels are burnt to IPS where carbon was captured.	HIGH	- -
		Regulation has set CO_2 emission targets for efuels more favorable than those adopted for crop-based biofuels.	MEDIUM	+
		The targets for alternative fuels (except for crop-based biofuels) are still to be reached given installed capacity.	MEDIUM	+
		There are incentives for the production/use of efuels.	HIGH	+ +
	Affecting competing technologies	Policy supports a broad range of competing technologies to reach emission targets.	LOW	+
		Regulation has favored hydrogen-related technologies and applications.	MEDIUM	- -
		Regulation is disincentivizing the production of crop-based biofuels.	LOW	+ +
	Affecting complementary technologies	It is more convenient for industrial companies to pay under the Emission Trading Scheme rather than invest in CCSU technologies.	HIGH	- -
4. Culture and society	Preferences, habits, demographics	Environmental sustainability and circularity are a priority in the eyes of the public.	LOW	+ +
		Individuals do not own a car relying on some form of shared mobility.	LOW	–
		Electric mobility is preferred to combustion engines (even though powered through net-zero impact fuels).	LOW	- -
	Biases and stigmas	CCSU technologies are not well perceived (especially by communities living closer to facilities and storage locations).	MEDIUM	–
		Engineered microbials used in industrial processes (i.e., not food-related) are well accepted by the public opinion.	LOW	+

A.1.3. Build socio-technical scenarios

After the interaction with other members of the eForFuel partnership and external industry experts, the most relevant sources of uncertainties were identified in three main areas, namely (a) CO_2 availability, (b) possible efuel applications, (c) formate economy. These are illustrated in Table A.3, together with the baseline scenario.

Table A.3
Output 1.D Socio-technical scenarios.

Analytical dimensions	Socio-technical scenarios
Baseline scenario	
1. Business environment	Efuels are used in air, maritime, and heavy-duty transport to complement other solutions (e.g., hydrogen and electricity) that might not be fully applicable for engines with high energy requirements. The market for formate has not grown significantly. Efuel producers are current Oil&Gas incumbents (who have reconverted their footprint and acquired relevant technologies) and some large player already active in alternative fuels. The market is structured on a regional basis, also considering locations that guarantee access to renewable energy and water. CCSU technologies have reached maturity for IPS, but not yet for DAC applications. Some players have emerged offering to industrial companies' services to manage captured CO2, including sales and utilization. These players are gas distributors, chemical companies, energy infrastructure companies, and digital platforms. CCSU infrastructure for transport and storage has developed in the most industrialized areas (e.g., industrial parks). GMMs can be sourced to many players. Efuels are distributed by current players in Oil&Gas and biofuel distribution, including integrated players. Some air/maritime transport companies have set up partnerships with efuel producers.
2. Science and technology	There is still not a dominant technological standard for efuel production. Other technologies for decarbonization (e.g., hydrogen and electricity) have developed rapidly, but not to the point of becoming the dominant technological solution for decarbonization (except for electricity in the passenger segment).
3. Policy and regulation	Policy and regulations are supportive to all technologies decarbonizing the transport sector.
4. Culture and society	Environmental sustainability and circularity are top priorities in the eyes of public opinion. All technologies moving in this direction (including microbials and CCSU) are well perceived.
Alternative scenarios	
Source of uncertainty (a): CO_2 availability	
The alternative scenarios posit significantly higher/lower availability of CO_2	
Scenario a1 (high): There is a mature CO_2 market with specialized players serving multiple industries/sectors for both technology provision and CO_2 management (sales and utilization). DAC CCSU technologies have reached maturity and infrastructures to store and transport CO_2 have been built at scale. Policy instruments such as the Emission Trading Scheme make it economically convenient for industrial companies to invest in CCSU technologies, which are amply accepted by the public.	
Scenario a2 (low): The CO_2 market is small and dominated by today's incumbents (i.e., chemical companies). IPS CCSU technologies are still not economically convenient and there is limited infrastructure in place. Policy has favored the new process/product technologies in hard-to-abate industries rather than supporting CCSU solutions, which are also poorly accepted by the public.	
Source of uncertainty (b): possible efuel applications	
The alternative scenarios posit a broader/narrower set of possible efuel applications.	
Scenario b1 (broad): Efuels are broadly used in air, maritime, and heavy-duty transport. Some residual usage is made also in the passenger segment. New players have entered the efuel industry (production and distribution). Other technologies for the decarbonization of the transport sector (e.g., electricity and hydrogen) cannot be applied in many segments because of limited power generation and lack of infrastructure. Policy and regulations are supportive to efuels (e.g., in terms of lifecycle assessment frameworks). Incentives are in place to produce/adopt them. Public opinion supports CO_2 circularity.	
Scenario b2 (narrow): Efuels are only used in air transport, where there is a high competition and abundance of offering. Electricity and hydrogen are the main solutions for the decarbonization of the transport sector. Policy and regulations are not supportive to efuels (e.g., in terms of lifecycle assessment frameworks). Public opinion does not favor engines that release CO_2 and other pollutants in the air despite CO_2 circularity.	
Source of uncertainty (c): formate economy	
The alternative scenarios posit formate to have broad/limited applications both in the energy and chemical sector.	
Scenario c1 (broad): Formate represents the main energy/hydrogen carrier. New applications have emerged in the chemical and pharmaceutical sector. The formate market has grown significantly, new players have entered the market.	
Scenario c2 (limited): The formate market has experienced a small growth limited to current applications. The production, storage, and distribution involve a small number of global players (i.e., large chemical companies).	

A.2. Defining ecosystem configurations

A.2.1. Analyze the structure of the ecosystem

In the analysis of the potential future ecosystem of eForFuel, the research team considered both the activities (rows) related to *technology development/provision* and those related to the process of *producing, distributing, and using efuels*. In terms of actors (columns), they included technology developers/providers and firms potentially involved in the process of supplying input (*upstream*), producing formate and the various kind of fuels (*production*), selling, distributing, and using efuels (*downstream*). Among the actors, the "CO_2 specialist" was added under the hypothesis that, whereas currently companies that develop CCSU technologies are also handling the captured CO_2, over time there will be increasing specialization as both technologies and the market mature.

In compiling the area of the matrix, possible trends were. These refer to industrial companies directly investing in technologies for the sustainability transition and to servitization of technologies and machineries. The results of the analysis are presented in Table A.4.

Table A.4
Output 2 A. Configuration matrix.

Activities		Actors														
		Technology developers/providers					Upstream			Production			Downstream			
		Carbon Capture technology provider	Electrolyzer technology provider	Biotech company	Bioreactor technology provider	Other technology provider	Electric energy supplier	Industrial company (e.g., cement, steel)	CO_2 specialist	Chemical company	Alternative fuel producer	Oil&Gas company	Fuel distributor	Fuel logistic (e.g., pipelines, terminals) provider	Air/sea/road transport company	Material/product manufacturer (e.g., plastics, cosmetics)
Technology development/provision																
Carbon Capture Technologies	Development	3	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Production/construction	3	–	–	–	–	–	–	–	–	–	–	–	–	–	–
	Commercialization/installation	3	–	1	1	–	–	–	–	–	–	–	–	–	–	–
Electrolyzer	Development	–	3	–	–	–	–	–	–	–	2	2	–	–	1	–
	Production	–	3	–	–	–	–	–	–	–	2	2	–	–	1	–
	Commercialization	–	3	–	1	–	–	–	–	–	2	2	–	–	1	–
GMMs	Development	–	–	3	–	–	–	–	–	–	–	–	–	–	–	–
	Production	–	–	3	–	–	–	–	–	–	–	–	–	–	–	–
	Commercialization	–	–	3	–	–	–	–	–	–	–	–	–	–	–	–
Bioreactor	Development	–	–	–	3	–	–	–	–	–	2	2	–	–	1	–
	Production	–	–	–	3	–	–	–	–	–	2	2	–	–	1	–
	Commercialization	–	1	–	3	–	–	–	–	–	–	–	–	–	–	–
Refinement technologies	Development	–	–	–	–	3	–	–	–	–	–	–	–	–	–	–
	Production	–	–	–	–	3	–	–	–	–	–	–	–	–	–	–
	Commercialization	–	1	–	–	3	–	–	–	–	–	–	–	–	–	–
Producing, distributing, and using efuels																
Renewable energy	Production	–	–	–	–	–	3	1	–	1	2	2	–	–	–	–
CO_2	Capture	3	–	–	–	–	–	2	3	1	–	–	–	–	–	–
	Transport	3	–	–	–	–	–	1	3	1	–	–	–	–	–	–
	Storage	3	–	–	–	–	–	1	3	1	–	–	–	–	–	–
	Sales and distribution	–	–	–	–	–	–	1	3	1	–	–	–	–	–	–
Formate	Production	–	–	–	–	–	–	1	–	3	1	1	–	–	–	–
	Transport	–	–	–	–	–	–	1	–	3	1	1	–	–	–	–
	Storage	–	–	–	–	–	–	1	–	3	1	1	–	–	–	–
	Sales and distribution	–	–	–	–	–	–	1	–	3	1	1	–	–	–	–
Efuels	Isooctane production	–	–	–	–	–	–	–	–	–	3	3	–	–	–	–
	Isododecane production	–	–	–	–	–	–	–	–	–	3	3	–	–	–	–
	Propane production	–	–	–	–	–	–	–	–	–	3	3	–	–	–	–
	Isobutene production	–	–	–	–	–	–	–	–	–	3	3	–	–	–	–
	Transport	–	–	–	–	–	–	–	–	–	2	3	3	3	–	–
	Storage	–	–	–	–	–	–	–	–	–	2	3	3	3	–	–
	Blending	–	–	–	–	–	–	–	–	–	2	3	3	3	–	–
	Sales and distribution	–	–	–	–	–	–	–	–	–	2	3	3	–	–	–
	Processing (if materials)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	3
	Usage	–	–	–	–	–	–	2	–	1	–	–	–	–	–	3

A.2.2. Formulate focal value propositions

A series of focal value propositions was formulated to account for the technological potential of eForFuel against different socio-technical scenarios (a synthetic version is presented in Table A.5).

Table A.5
Output 2B. Scenario-dependent focal value propositions.

Socio-technical scenarios	Focal value propositions
Baseline	*Baseline – Partnering with the fuel industry towards greener pathways* - eForFuel provides technological solutions enabling Oil&Gas firms to reconvert their production footprint from fossil sources and alternative fuel producers to further develop their offering
a1	*a1– Supporting CO_2 circularity across industries* - eForFuel provides technological solutions to utilize CO_2 (IPS and DAC) to produce fuels, gases, materials (e.g., plastic, rubber), and products (e.g., cosmetics)
a2	*a2– Enabling industrial players to embrace CO_2 circularity* - eForFuel allows industrial players in hard-to-abate industries to reuse their captured CO_2 by providing relevant technology and process expertise
b1	*b1 – Providing advanced technologies for efuel production* - eForFuel provides efuel producers (Oil&Gas and alternative fuel incumbents, new players) with technological solutions for producing fuels with various applications
b2	*b2 – Reducing emissions in the air transport industry* - eForFuel provides greener fuels produced thanks to innovative technologies to air transport firms
c1	*c1 – Enabling the formate economy* - eForFuel provides technological solutions for both producing formate from CO_2 and processing formate into efuels and materials
c2	*c2 – Enabling integrated and flexible efuel production* - eForFuel provides technological solutions to produce efuels from CO_2, allowing process flexibility thanks to the production of formate as an intermediate step

The focus of eForFuel on technology is a common theme along all focal value propositions. Differences concern: the technological scope (**c1, b2**), the product portfolio (**a1**, **b1**), and the presence of value propositions beyond technology development (**a2**, **b2**). These differences determine the shape and boundaries of the eForFuel ecosystem, as illustrated below.

A.2.3. Define ecosystem configurations to deliver scenario-dependent focal value propositions

Based on the different value propositions (Table A.5), seven ecosystem structures were defined and graphically represented in flowcharts. On the baseline scenario (Fig. A.1), scenario-dependent variations were introduced (Fig. A.2, Fig. A.3., Fig. A.4).

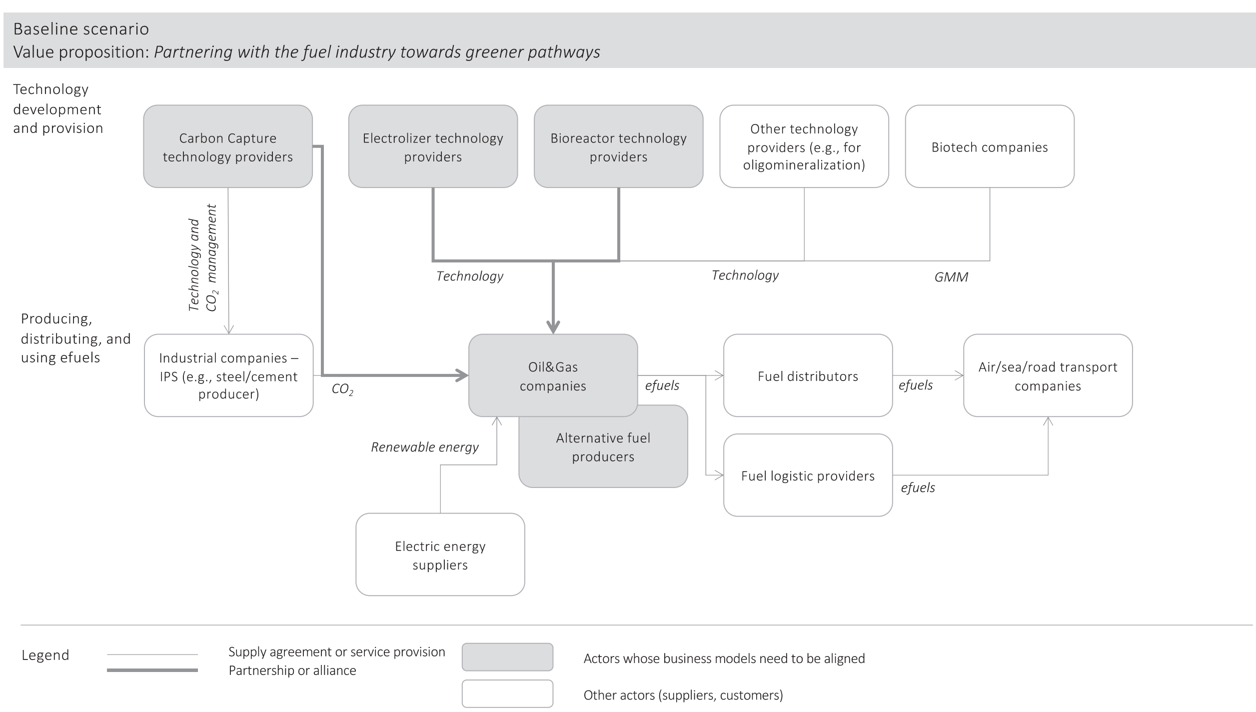

Fig. A.1. – Output 2C. Ecosystem structure flowcharts (baseline scenario).

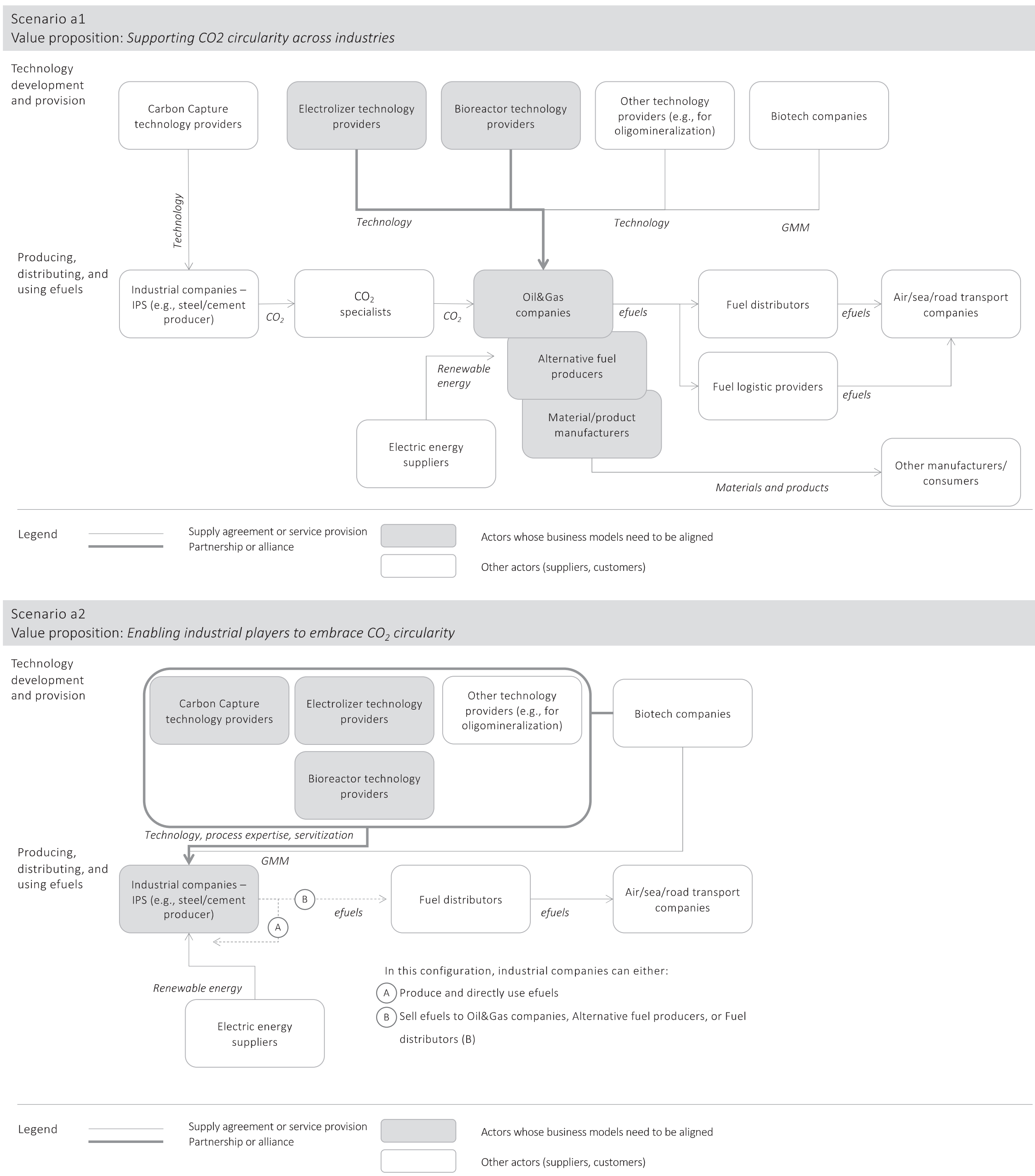

Fig. A.2. – Output 2C. Ecosystem structure flowcharts (depending on CO_2 availability).

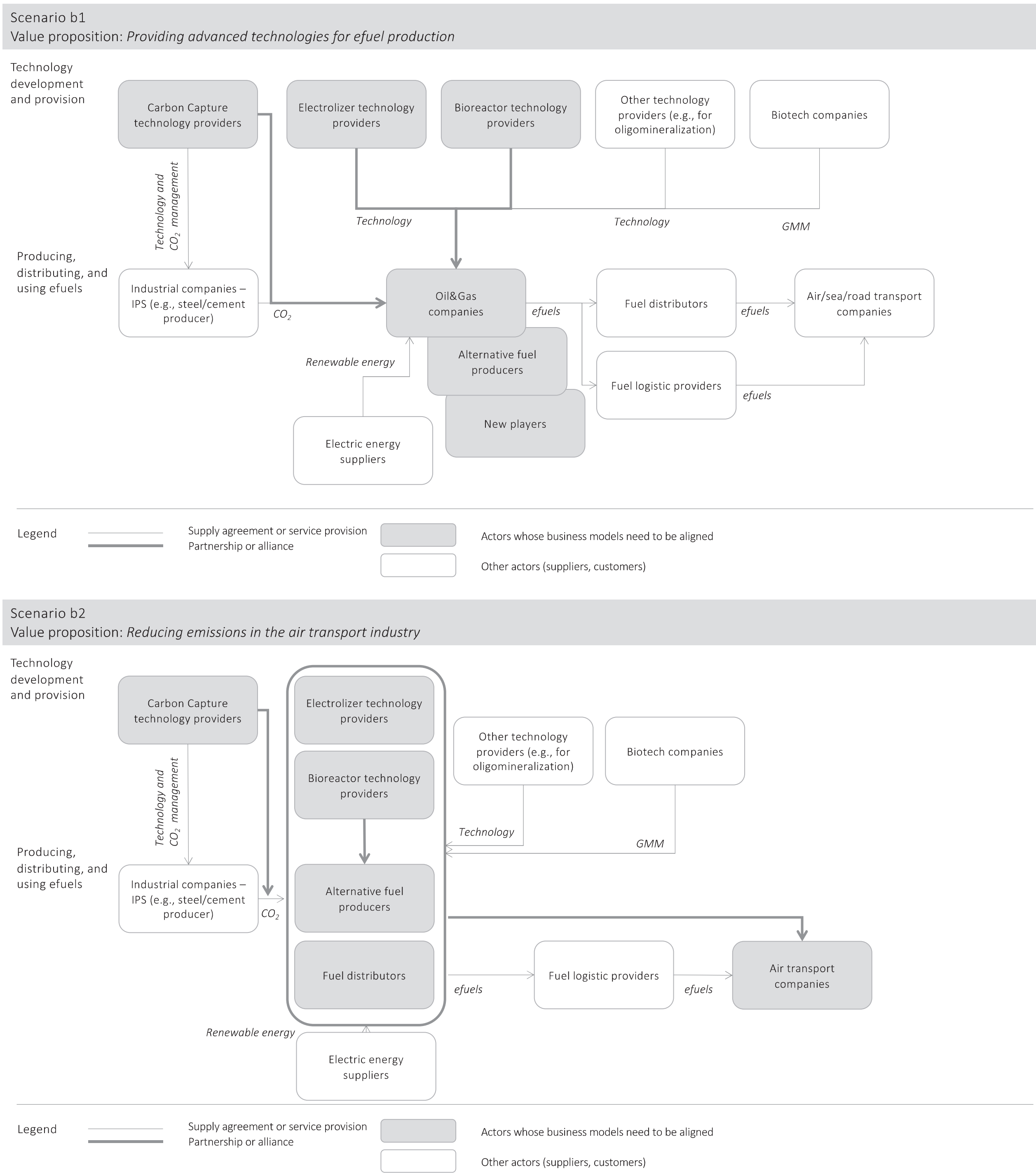

Fig. A.3. – Output 2C. Ecosystem structure flowcharts (depending on efuel application).

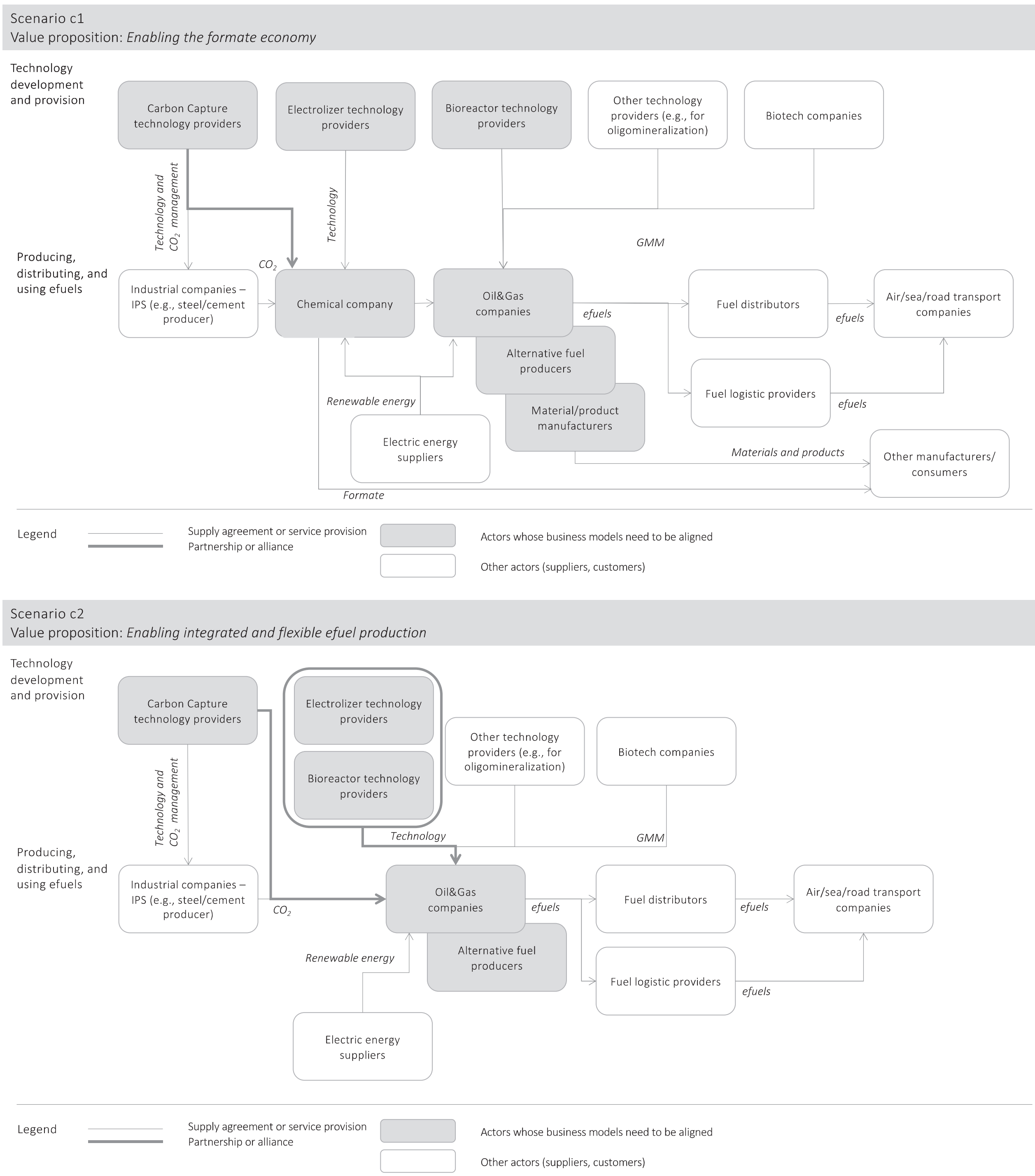

Fig. A.4. – Output 2C. Ecosystem structure flowcharts (depending on formate economy).

The ecosystem structure for the **baseline** scenario (Fig. A.1) shows the importance of pursuing alignment (e.g., through partnership agreements) between technology providers (carbon capture, electrolyzer, bioreactor) and fuel producers (Oil&Gas companies and alternative fuel producers). This can facilitate the adoption of eForFuel solutions given the lack of a dominant technological standard. Moreover, CCSU technology providers should be involved to ensure CO_2 supply and possibly cooperate in building relevant infrastructure, especially in the most industrialized areas. This appears consistent with their current business model.

Configurations for different levels of CO_2 availability: As for the two scenarios positing different CO_2 availability, **a1** posit the existence of a CO_2 market and related specialists (e.g., companies specialized in handling, storage, and commercialization). In this context, there might be increasing interest in finding options to use CO_2. In this sense, material/product producers were included in the ecosystem, whereas partnerships to secure CO_2 supply were not deemed relevant. With respect of **a2**, we considered that industrial companies might need support to adopt CCSU, so that CO_2 utilization might provide a compelling argument against storage costs. In this respect, it might be relevant to establish partnerships among relevant technology providers for providing turn-key solutions, process expertise or even servitization options.

Configurations for different possible efuel applications: In terms of the effects of the range of efuel applications, **b1** is grounded on a similar logic than the baseline scenario but considers that new players might be attracted by the opportunity. The partnership among technology providers is meant to develop advanced and comprehensive solutions in a growing market. The configuration for **b2** assumes a highly competitive market for air transport efuels. Alliances among technology providers, fuel producers and distributors, and air transport companies can support the development and adoption of decarbonization solutions.

Configurations for different maturity levels of the formate economy: The last two configurations are based on the uncertainties related to the formate market. The configuration for scenario **c1** pairs electrolyzer technology providers with chemical companies for formate production, whereas bioreactor technology providers are serving efuel producers and material/product manufactures. Alignment structures between developers and users of technologies are meant to facilitate adoption and improvement. For **c2**, the logic is consistent with the baseline scenario but stresses the need to offer integrated solutions enabling more flexible production processes (e.g., formate might be stored until renewable energy is available at a convenient cost).

The analysis of commonalities and differences among the scenario-dependent configurations highlighted that electrolyzer and bioreactor technology providers need to proceed together, besides in the case of a significant growth in the size of the formate market (**c1**). The early involvement of CCSY technology providers is also needed, unless there will be an acceleration in technological maturity, including DAC technologies (**a1**). Industrial players assume the role of key customers only in case of a low maturity of CCSU (**a2**). The involvement of customers (i.e., airline transport companies) become relevant only against a high level of competition in technology provision determined by a narrow range of efuel possible applications.

A.3. Designing integrated business models for the firms within the ecosystems

A.3.1. Define firm-level business model options

The position of each firm within the different ecosystem configurations were analyzed. As the context and the key relationships (i.e., partners, suppliers, customers) are already outlined in the scenarios and in the flowcharts, the business models were explained in terms of key activities, revenue streams and costs in output 3 A (Business model playbook). Only players that according to the analysis of ecosystem configurations needed to align their business models are included. For example, the analysis highlighted that biotech companies providing GMM are numerous and thus the relationship can be handled through market mechanisms. Table A6 presents a summary.

Looking at the bioreactor technology provider for illustrative purposes, the value propositions highlight the need to offer cutting-edge solutions. Scenario **c1** posit a limited coordination with the electrolyzer technology provider, whereas the other scenarios show integration between the two technologies. Potential partnerships with air transport companies (scenario **b2**) might imply revenue streams from licensing. In scenario **a2**, the ecosystem focal value proposition is oriented towards supporting industrial companies in investing in CCSU and CO_2 handling, the bioreactor technology provider needs to cooperate with other players for turn-key solutions and integrated process expertise. These options affect both revenue streams and the cost structure due to a different scope of operating activities.

Table A.6
– Output 3 A. Business model playbook (summary version).

	Firms involved in the scenario-dependent ecosystem configurations									
	Carbon Capture technology providers	**Electrolyzer technology providers**	**Bioreactor technology providers**	**Industrial companies**	**Chemical company**	**Oil&Gas companies**	**Alternative fuel producers**	**Material /product producers**	**Fuel distributors**	**Air transport companies**
Firm-level value proposition										
Baseline scenario	Delivering solutions for industrial players to handle CO_2	Developing and providing cutting-edge technologies for the production of efuels				Delivering high-quality fuels with low environmental impact (no fossil, no crop-based biomasses)				
Alternative scenarios a1		Developing and providing cutting-edge technologies for the production of efuels				Delivering high-quality fuels with low environmental impact (no fossil, no crop-based biomasses)		Delivering cleaner materials and products		
a2	Providing cost-effective turn-key solutions for industrial players to handle and utilize CO_2			Delivering high-quality product with						

(*continued on next page*)

Table A.6 (*continued*)

	Firms involved in the scenario-dependent ecosystem configurations									
	Carbon Capture technology providers	**Electrolyzer technology providers**	**Bioreactor technology providers**	**Industrial companies**	**Chemical company**	**Oil&Gas companies**	**Alternative fuel producers**	**Material /product producers**	**Fuel distributors**	**Air transport companies**
				low environmental impact						
b1	Delivering solutions for industrial players to handle CO_2	Developing and providing cutting-edge technologies for the production of efuels				Delivering high-quality fuels with low environmental impact (no fossil, no crop-based biomasses)				
b2	Delivering solutions for industrial players to handle CO_2	Providing cost-effective technological solutions to lower emissions in the air transport industry					Supporting the air transport industry in lowering emissions		Supporting the air transport industry in lowering emissions	Operating with the lowest possible emissions and costs
c1	Delivering solutions for industrial players to handle CO_2.	Developing and providing cutting-edge technologies for the production of formate	Developing and providing cutting-edge technologies for processing formate		Delivering green formate to a wide range of industries	Delivering high-quality fuels with low environmental impact (no fossil, no crop-based biomasses)		Delivering cleaner materials and products		
c2	Delivering solutions for industrial players to handle CO_2	Developing and providing cutting-edge technologies for the production of efuels				Delivering high-quality fuels with low environmental impact (no fossil, no crop-based biomasses)				
Possible revenue streams related to eForFuel	Sales of technology, related services, and CO_2 handling Possible fees related to CO_2 processing (scenario a2)	Sales of technology and related services Possible fees related to CO_2 processing (scenario a2) Possible licensing of technology (scenario b2)		Sales of efuels and other products from CO_2 utilization	Sales of green formate	Sales of efuels	Sales of efuels	Sales of materials and products with lower emissions	Logistic fees	Fees related air transport services (licence to operate/ price premium)
Possible costs related to eForFuel	Technology development and provision CO_2 logistics and infrastructure Operating costs of processing (in scenario a2)	Technology development and provision Operating costs of processing (in scenario a2)		Investment in technology Savings on carbon-related taxation Operating costs of processing (in scenario a2)	Investment in technology Savings on carbon-related taxation Operating costs of handling CO_2	Investment in technology Investment in plant upgrading, dismissal and new plants Savings on carbon-related taxation Operating costs of handling CO_2		Investment in technology Savings on carbon-related taxation	Depending on new plant location	Price premium Savings on carbon-related taxation Costs related to technology licensing

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