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Development of a method of analysis to identify emerging dominant designs in the aircraft powerplant industry

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Abstract

Commercial aviation will face demanding challenges in the near future. Sustainability both in environmental and economic terms requires technological changes.

The purpose of the analysis is to identify through a structured method the most likely dominant design of aircraft powerplants in 2040. The main driver is an appropriate situation awareness of the context, beyond purely numerical data.

The method is divided into three main phases.

A qualitative analysis, with an overview on the competing present and future technologies and their variants. It also focusses on the market segments served, and on the complementary assets needed.

A semi-quantitative analysis, that highlights the lead-lag correlations between each considered technology, and each respective core technology it is based on. It evaluates then the degree of interaction each technology can show with the market.

A quantitative analysis based on actual data about each technology to predict the trends of their performance and innovation curves.

Qualitative and semi-quantitative analyses leverage on an adaptation of the *CFTP technique*, while quantitative analysis on the *Technology Forecasting technique*.

Results suggest that once Hydrogen production and management technologies will be mature enough, they will allow liquid Hydrogen-based powerplants to become dominant, at least for the most relevant market segment in terms of traffic and emissions: operators interested in short to medium-range flights and low payload capacity.

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Introduction

This work aims at identifying the emerging dominant design of future aircraft powerplants. The topic is very broad, therefore some clear boundaries limiting the envelope of the analysis will be set, and they will be explained in Chapter 3.

The structure of the thesis foresees an introductory chapter describing the framework in which the analysis moves its steps. Each paragraph of the chapter will be introduced by the key definitions characterizing it.

Then, the most common technology forecasting models will be discussed; an algorithm based on them and tailored on the specific case study will be explained.

Later, the discussion will dive onto the case study, and the algorithm will be applied.

Finally, conclusions will be drawn, and a general overview will be suggested.

1. General framework

1.1 Technological lifecycle (TLC) and performance S-curves

Key definitions:

I. *Technological lifecycle (TLC):*
"The period from a major breakthrough opening up a new territory for exploitation to the next major barrier. It is characterized, in part, by a high initial marginal productivity of R&D, and a more or less continuous decline thereafter, as the territory is gradually exhausted." (Ayres, 1987).

II. *Technological frontier:*
"The highest level reached upon a technological path with respect to the relevant technological and economic dimensions" (Dosi, 1982).

III. *Technological discontinuity:*
Situation where "an innovation:
   a) pushes forward the performance frontier along the parameter of interest by a significant amount, and
   b) does so by changing the product or process design" (Anderson & Tushman, 1990).

A technological discontinuity determines cost or quality advantages aiming directly not at the margins of an industry, but at the core aspects of it.

IV. *Technology push:*
Determinant of technological innovation such that technology is developed "as an autonomous or quasi-autonomous factor, at least in the short run" (Dosi, 1982). Thus, in a technology push environment, innovation is mostly independent from the market.

V. *Demand pull:*
Determinant of technological innovation such that technology is developed according to signals of market forces.

According to Ayres, TLC enjoys five main phases; each of them shows different approaches, in particular towards standards, scale and process technology (Table 1).

Life cycle stage	*Diversity versus standard*	*Scale and process technology*	*Labor require-ments*	*Logistics, transport, inventory, handling, technology*
INFANCY	Unique	Custom; *ad hoc* multi-purpose machines	High labor intensity, high-skilll workers needed	Little concern w/ inventory, low relative cost of trans-port, manual handling
CHILDHOOD	Diversity of types & imitators	Small batch job shop, manual operation	Expansion of labor force, but minimal "deskilling"	Inventory costs increase sharply, transport cost increase, manual handling
ADOLESCENCE	Increasing standardiza-tion, fewer models; faster diffusion	Medium to large batch; special machines & fixtures	Embodiment of labor skills in machines	High inventory, high transport costs, semi-auto handling
MATURITY	High degree of standardi-zation, approaching saturation	"Mass"; dedicated mechani-zation, transfer lines etc.	Low labor intensity, low skill for direct mfg. jobs; High skill for indirect & managerial jobs	Reduced inventory, high transport, mechanized handling
SENESCENCE	Commodity-like			

Table 1. TLC phases (Ayres, 1987).

Technological lifecycle can be represented as a curve, with time, cumulative R&D effort, or cumulative revenues of the industry on the horizontal axis and a performance index on the vertical axis. The model is consistent with an "S-shaped curve".

The first part of the life of a new technology usually corresponds to the highest performance over cumulative R&D effort ratio (the highest slope of the curve).

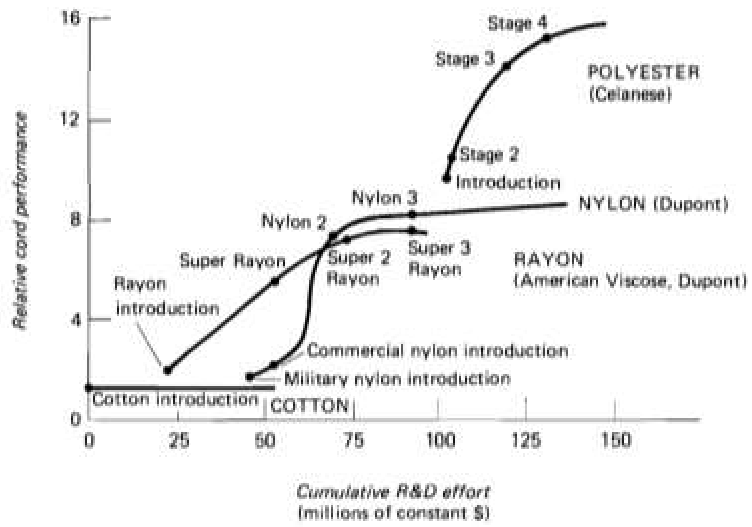


Figure 1. Performance curves for tire cord technologies: cotton, rayon, nylon, and polyester (Ayres, 1987).

As shown in Figure 1, the first 60 M $ invested on rayon technology R&D generated about 800% increase of the performance for such technology, the next 15 M $ resulted in a 25% performance increase, while the last 25 M $ in just a 5% improvement. An even clearer example of an S-curve is offered by the nylon technology performance curve.

The concept of S-curves runs across a dualism of two complementary phases that can be identified with many different peers of terms, depending on the perspective.

The two main phases along an S-curve are: the *revolutionary phase* and the *evolutionary phase*; they correspond to *exploration* and to *exploitation* of the capabilities of such technology, respectively.

In the revolutionary phase a new technology emerges after an initial period of uncertainty (exploration). A technological discontinuity allows a clear definition of the main technology that is going to dominate a market.

The evolutionary phase is instead focused on improving a now established technology to push forward its technological frontier (exploitation).

According to Dosi, there is a continuous alternation of evolutionary and revolutionary innovation phases in the history of an industry. First, a new technology needs to become sufficiently mature to compete and possibly substitute incumbent technologies: this is the revolutionary phase. Then, the focus moves to improvements of such technology until it reaches its limit: the evolutionary phase. After that, a newer and higher performing technology may take the place of the older one. Therefore, the history of an industry can be analyzed from a performance perspective as a sequence of S-curves, as in Figure 1. Improvements along the same S-curve are linked to the evolutionary phase, while the shift from an S-curve to the next one is a revolutionary phase.

Another distinction is between *technology push* and *demand pull*. They are drivers that, according to the abovementioned dualism, can alternatively push or pull development. In fact, technology pushes innovation when it is about a new undiffused technology aiming at establishing itself on the market, while demand pulls innovation when a technology is well known by a market that requires products embedding a state-of-the-art of such technology.

The economic implications of innovation can be shown, for instance, by considering investment returns during a typical product life cycle curve, as in Figure 2.

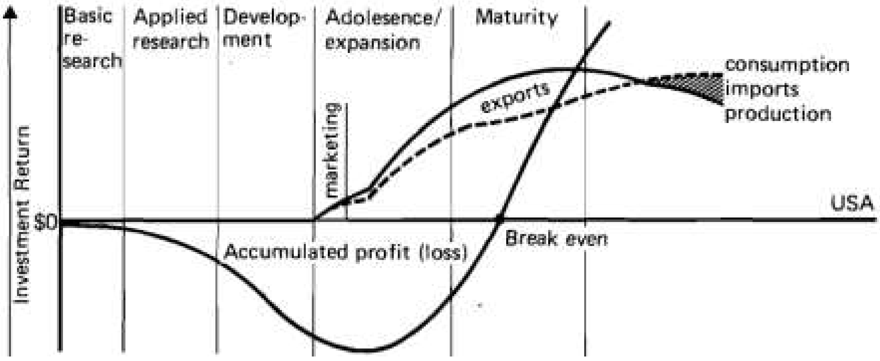


Figure 2. Product life cycle (adapted from Ayres 1984).

The first three phases labeled by Ayres are characterized by high R&D levels, and investment returns are negative. But they start to grow as diffusion of the products related to the considered technology becomes appreciable.

The very first prototype of a product is built after a technological barrier is overcome. Then, many years may elapse from the basic research study on such technology to the development of an effective prototype, and finally to mass production.

There are often several false starts that slow down the process. To stay on the same topic of the case study considered in the thesis, an example is the history of flight: the first systemic study and research on flight have their roots in the XV Century, but technological and knowledge barriers prevented the first flight of a vehicle "heavier than air" (i.e., a vehicle capable of flight thanks to the lift generated by its surfaces instead of the buoyancy linked to Archimedes' principle) until the beginning of the XX Century. Wright brothers' Flyer first flight was in 1903, but a first model of a mass-produced aircraft was available only many years after. Once the operative barriers are overcome, progress becomes rapid.

The Pasteur quadrant.

About the categories of research than can be performed considering the trade-off between the ability to answer the need for fundamental understanding and the immediate use for society, it is worth to mention the Pasteur quadrant, introduced by Donald E. Stokes. Research activities can be classified into:

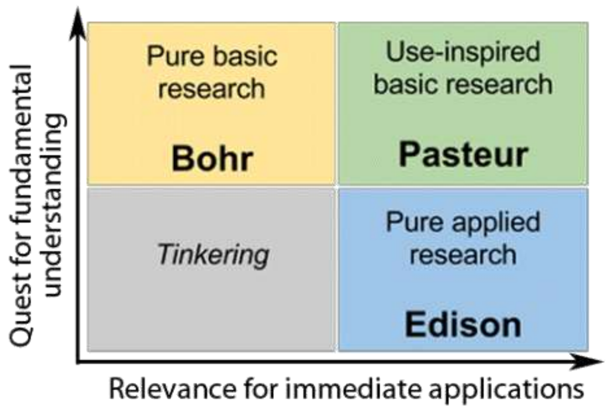


Figure 3. The Pasteur quadrant (IDfuse).

1.2 Technological paradigms

Key definitions:

I. *Technological paradigm:*
"An 'outlook', a set of procedures, a definition of the 'relevant' problems and of the specific knowledge related to their solution. A 'model' and a 'pattern' of solution of selected technological problems." (Dosi, 1982).

II. *Technological trajectory:*
The direction of advance within a technological paradigm. "A technological trajectory [...] can be represented by the movement of multi-dimensional trade-offs among the technological variables which the paradigm defines as relevant. One could thus imagine the trajectory as a 'cylinder' in the multidimensional space defined by these technological and economic variables. (Thus, a technological trajectory is a cluster of possible technological directions whose outer boundaries are defined by the nature of the paradigm itself)" (Dosi, 1982)

Technological paradigm is a model proposed by Dosi in 1982 to explain technology and its life cycle in a broad sense.

Technological paradigms are problem-specific: each paradigm is shaped and dependent on the problem it is related to. The problem to be solved is economically defined as "need". So, new paradigms emerge when new or different needs emerge.

Technological paradigms are also linked to an exclusion effect, since every selected and developed technological trajectory leads to the exclusion of others.

Among the many variables affecting a technological paradigm the most relevant ones are:

- generic tasks the paradigm focusses upon; it is the attempt to satisfy a need;
- materials selected;
- physical and chemical properties exploited;
- technical and economic dimensions considered;
- trade-offs accepted by the market and by the producers.

Therefore, a paradigm collects many elements both from the supply-sided and demand-sided actors and from their environment:

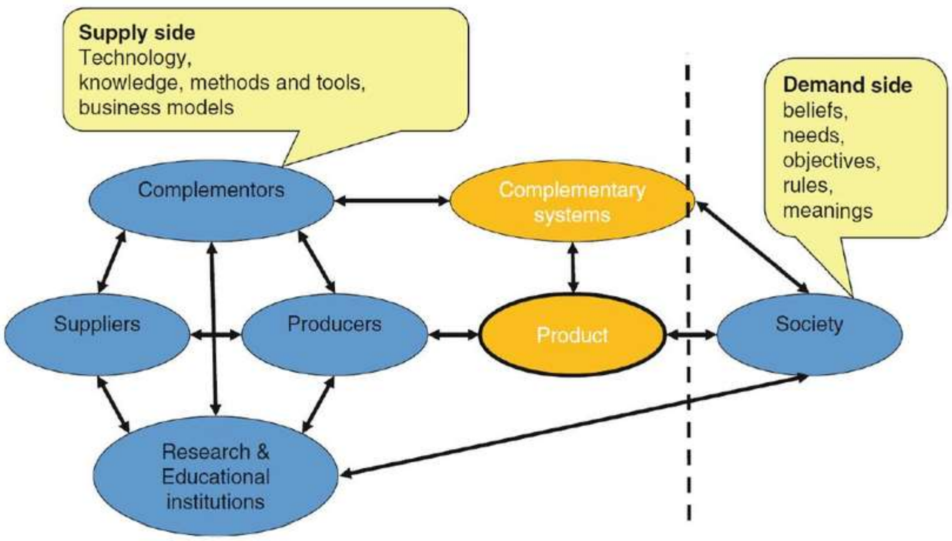


Figure 4. The constituent elements of a technological paradigm (Cantamessa, Montagna, 2016).

Those elements need to be managed and integrated by producers on the supply side, and by consumers on the demand side.

In particular, *complementors* are the operators providing complementary products and services that contribute to such integration. At the same time, *meanings* help define the value of a product on the supply side beyond its technical performance through subjective elements affecting the degree of interest and the value attributed by consumers to the product.

Each technological paradigm follows a trajectory during its life.

According to Dosi, technological trajectories show some basic features:

- trajectories can be different in terms of specificity and "power" (the capability to effectively and efficiently satisfy a need);
- complementarities exist among trajectories and, inside each trajectory, among different fields of knowledge and skills;
- each trajectory current apex is represented by its technological frontier;
- progress along a technological trajectory is also affected by the starting position of an actor (e.g., a firm) in terms of know-how and relative distance with respect to the current technological frontier;
- the more a trajectory is established and "powerful", the higher the cost, in broad sense, of switching from such trajectory to an emerging one; in particular, if the frontier of the newer trajectory is remarkably behind the frontier of the older one, switching costs are even higher, because investments on the development of the problem-solving activity are required to match the frontier of the incumbent technology;
- the capability to compare *a priori* two or more technological paths with reliable assessments is limited. Better results can be obtained ex post by considering specifically selected indicators.

Dosi's paradigm model can be summarized with three main implications.

"It can explain the role of *continuity* versus *discontinuity* in technical change" (Dosi, 1982), in analogy with the comparison between exploration and exploitation concepts, but from a slightly different perspective. It also redefines the concepts of *incremental innovation* and *radical innovation*: the former is the pure exploitation process of a technology; the latter is the emerging of a new paradigm.

Second, the idea of paradigm allows to have a systemic overview of the procedures leading to technological change.

Third, the model enables analysts to better understand and predict both evolutionary and revolutionary phases in an industry. However, ex ante evaluations are still effort-demanding and only partially reliable, but such degree of uncertainty can be perceived more clearly thanks to the paradigm concept.

1.3 Classification of innovations

Innovations can by classified depending on the focus of the analysis. As before, a dualistic approach emerges. Changes in definitions depend on peculiar innovation areas that are considered, but every criterion is located on one of the two sides of the line that separates evolutionary and revolutionary phases of a technology.

		Phase	
		Evolutionary	**Revolutionary**
Criterion	**Product and its technical tradeoffs**	*Incremental innovation*	*Radical innovation*
	Producer and its organizations	*Competence-enhancing innovation*	*Competence-destroying innovation*
	Product architecture	*Peripheral innovation*	*Core innovation*
	Business impact	*Sustaining innovation*	*Disruptive innovation*

Table 2. Innovation types matrix.

1.4 Innovation, product architecture, producer and its organization

Key definitions:

I. *Product architecture:*
The set of mutual relationships among components of a product.

II. *Competence enhancing innovation:*
"It builds on know-how embodied in the technology that it replaces. For example, the turbofan advance in jet engines built on prior jet competence" (Anderson, Tushman, 1990).

III. *Competence destroying innovation:*
"A competence destroying discontinuity renders obsolete the expertise required to master the technology that it replaces" (Anderson, Tushman, 1990).

An innovation path cannot ignore the architecture of the product that applies a considered technology, because a change in the architecture affects processes and routines. Therefore, it reshapes production from an organizational point of view.

According to Henderson and Clark, the relationship between the reference technology and the architecture of a product can be classified in four types, as shown in Table 3.

		Architecture	
		Do not Change	**Change**
Reference technology	**Change**	Modular innovation	Radical innovation
	Do not Change	Incremental innovation	Architectural innovation

Table 3. Innovation and product architecture matrix.

- Modular innovation:

New technologies are introduced at component level, but the relationships between those components and the rest of the system are not affected.

Example: the shift from analogic to digital cockpit instrumentation on aircrafts and cars.

- Incremental innovation:

Component-level technologies and product architecture are not changed; it is pure exploitation and improvement of the capabilities of existing technologies.

Example: internal combustion engine improvements.

- Architectural innovation:

Product architecture changes, reference technologies do not. In general, producers mostly innovate along a modular rather than an architectural approach, because the latter implies a change in the routines of the production process, thus a change in the organization.

Example: internal combustion engine car with “sandwich” chassis.

- Radical innovation:

Innovation affects both reference technologies and product architecture. Based on the classification of Table 2, such innovation is at the same time radical from a product point of view, competence destroying from an organizational point of view, and core-related from an architectural point of view.

Example: electric cars with battery packs embodied into the chassis.

1.5 Innovation and business impact

Key definitions:

I. *Disruptive innovation:*
Innovation that, when diffusing, changes the balance of power and market share of producers.

II. *Total customer responsiveness:*
The capability to offer secondary products and/or services that satisfy all-around needs related to a reference product. As example, a widespread service network offered by a car brand is a complementary asset that contributes to total customer responsiveness around the purchase of a vehicle.

From a business impact perspective, innovation can be disruptive or sustaining, as seen in Paragraph 1.3.

In an environment disrupted by an innovation incumbents fail to effectively counteract the actors who are betting as first-movers on a new technology.

In this paragraph the main reasons leading an innovation to be disruptive will be discussed according to Cantamessa's and Montagna's analysis. Similarly, reasons that can cause failure of such disruptive potential will be considered.

Disruptive innovation.

The causes leading to a situation of disruptive innovation are different among them and at least partially interdependent.

The first reason is the inability by the incumbents to join a new paradigm. An innovative technology can be capable of satisfying growing or new customer needs, while the incumbent technology cannot. Therefore, a paradigm change may occur. *Action inertia* - the insufficient capability of appropriate reaction to a new emerging paradigm - is a factor that can foster such phenomenon. Supporters of the incumbent technology may suffer misaligned resources, organizational inertia, and generally path dependency. Then, a second factor is *cognitive inertia*, defined as the inertia in understanding the change of paradigm. That is due to four main *cognitive traps*:

- When in a competitive environment, a technology manages to overcome competitors, the lack of willingness to destroy achieved competence can hinder the shift to a new paradigm: supporters of a winning technology might be erroneously convinced of being the holders of the best possible technology, failing to foresee threats from incoming technologies.

- *Sunk cost trap*: the decision to jump on a new technology is affected by the need to exploit investments on the current technology that are considered as sunk costs from a financial perspective.
- *Status quo trap*: if the focus of a firm is uniquely on the status quo, when it will enjoy a new paradigm performance will be low.
- *Incentive trap*: employees' effort is limited by the lack of incentives linked to firm growth.

The second main reason is the so-called *Christensen effect*, where incumbents keep concentrating on reference markets and powerful customers, in terms of market share and stability; at the same time new technology developers focus on unmet or new needs, and on neglected market segments. It is difficult to accurately predict when the performance of new technology will be sufficient to also satisfy the needs of the reference markets, because early profits from the new-technology products can be effectively reinvested, thus reshaping the performance S-curve and causing the slope of the new technology curve to change unpredictably.

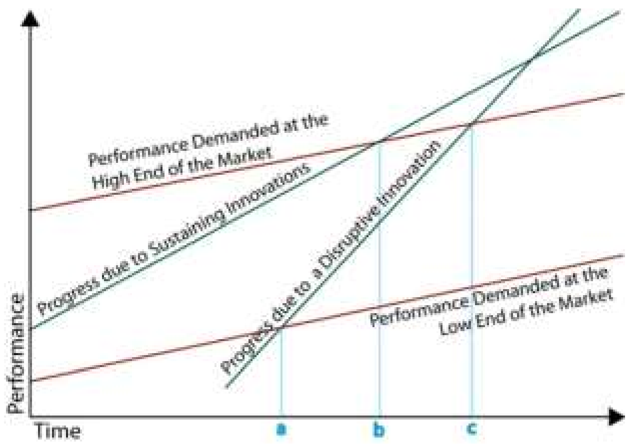


Figure 5. The Christensen effect (Biznews).

Third, incumbents and supporters of a new technology pursue different goals: the incumbents aim at maximizing profits, while new entrants at probability of survival. Therefore, timing of strategic decisions about adoption and development of new technologies can be different.

Non-disruptive innovation.

First-mover advantage is not enough to guarantee success. There are some factors that determine an unsuccessful business outcome of an innovation.

The first one is the limited forecasting power.

Radical innovations are such from a technical point of view, but that does not imply that they are also disruptive from a business point of view. Forecasting power is limited because many variables can affect markets and business environment. Nested S-curves (*product generations*) can cloud the capability to identify saturating technologies.

Forecasting power also depends on the parameter considered as the independent variable of the S-curve: if time is considered on the horizontal axis, it can hinder the sight of potential residual margin for performance improvements; if cumulative R&D investments are considered instead, it is easier spot a possible *sailing ship effect*. It is a phenomenon that can happen when a new technology enters the market causing the risk for incumbent technologies to disappear. Incumbent may make investments on improvements of the old-technology product to allow its performance curve to climb enough so that it will not be crossed by the new-technology curve, at least in the short term. Incumbents also retreat the application of their old-technology products to areas where the new technology is still immature to compete with them. A typical example is indeed the reaction of the sailing ship builders when steam ships (no wind-dependent but range-limited technology) entered the market. Incumbents improved the performance of their sailing ships and focused on long range freight transport.

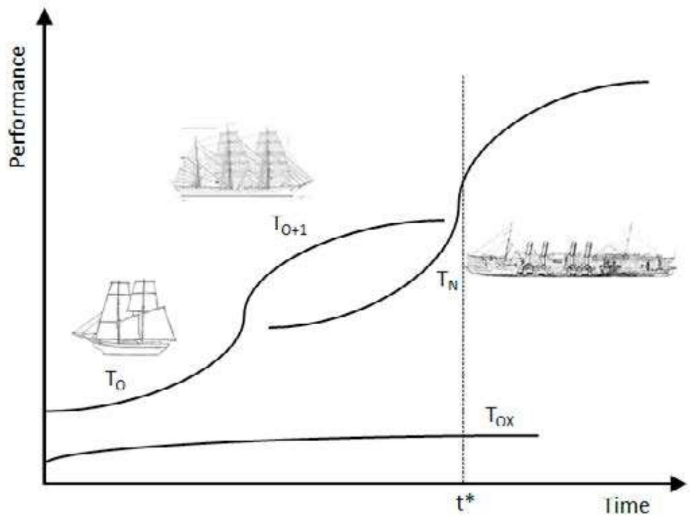


Figure 6. The sailing ship effect (Beckmann, Royer, Schiavone, 2016). T_O: old technology; T_{O+1}: improved old technology; T_N: new technology; T_{OX}: skipped technologies because less performing.

The second reason can be explained by the theory of *localized technological chan*ge. "For each given technology and a variety of possible locations in different economic systems with different relative prices, there is always a best solution and consequently a ranking of locations. The best location clearly provides the most abundant supply of the most productive factor. Conversely it is also clear that for each location, and hence each system of relative prices, there is always a better technology. […] Technological change is introduced locally by firms able to learn about the specific techniques in place and hence to improve them." (Antonelli, 2004). Customers are willing to switch to a new technology only if "utility" of it is higher than "utility" of the previous technology. The former is affected by a balance between cost and revenues, and by switching costs when shifting from the "old" product to the "new" one and vice versa; the latter is mainly characterized by a balance between cost and revenues, by the experience gained with the "old" products, and by the existence of complementary assets.

Innovators might also neglect market-making, defined as the set of actions undertaken to drive potential customers towards the new technology and to make them assign a high value to the new products. So, they might neglect to increase the “utility” of their products in the eyes of potential customers.

A third factor is appropriability and complementary assets. Appropriability represents the level of inimitability of a specific technological knowledge. The more a technology is easily imitable, the higher the risk of failing on the market, despite the offered products are innovative. Complementary assets contribute to creating a network of ancillary products or services pivoting around the focus product. The more such network is attractive and capable of achieving total customer responsiveness, the higher is the utility of the product.

Finally, business success of an innovation depends also on strategies of the incumbents: they can decide to pursue exploitation of the current business model, or to adopt a disruptive business model, or to do both, or to stay still. Depending on such decision, four main strategies can be identified, as in Table 4.

		Exploration of current business model	
		Yes	**No**
Adoption of disruptive business model (exploration)	**Yes**	Pure exploration	Integration
	No	Defiant Resistance	Pure exploitation

Table 4. Strategies of incumbents.

Boumgarden (2009) identifies two main approaches by incumbents, instead: ambidexterity and organizational vacillation.

		Characteristics	Pros	Cons
Approach	**Ambidexterity**	Exploitation of the current business model and exploration of a new one in parallel. The goal is a stable balance between exploration and exploitation.	Smooth change. The firm can enjoy complementarities between exploration and exploitation.	More complex organization, often with new business units characterized by different KPIs and managerial criteria. More structural tension between exploration and exploitation.
	Vacillation	Sharp shift from the current business model a the new one. The goal is to achieve maximum possible results in exploration and exploitation.	No risk of compromising exploration and exploitation performances while trying to balance them.	Sudden alternation of phases. Benefits in terms of increased performances in exploration and exploitation are difficult to assess.

Table 5. Strategies of incumbents according to Boumgarden.

Generally, complementary assets and total customer responsiveness can play a vital role both for an innovation to be successful, and for an incumbent technology to have enough inertia to withstand the threat of substitute technologies.

1.6 Product diffusion and customer segments

Key definitions:

I. *Diffusion effect:*
"The cumulatively increasing degree of influence upon an individual to adopt or reject an innovation, resulting from the activation of peer networks about the innovation in the social system. This influence results from the increasing rate of knowledge and adoption or rejection of the innovation in the system" (Rogers, 1982).

If plotted over time on a frequency basis, adopter distribution curve follows a normal, bell-shaped curve; if plotted on a cumulative basis, it follows an S-curve.

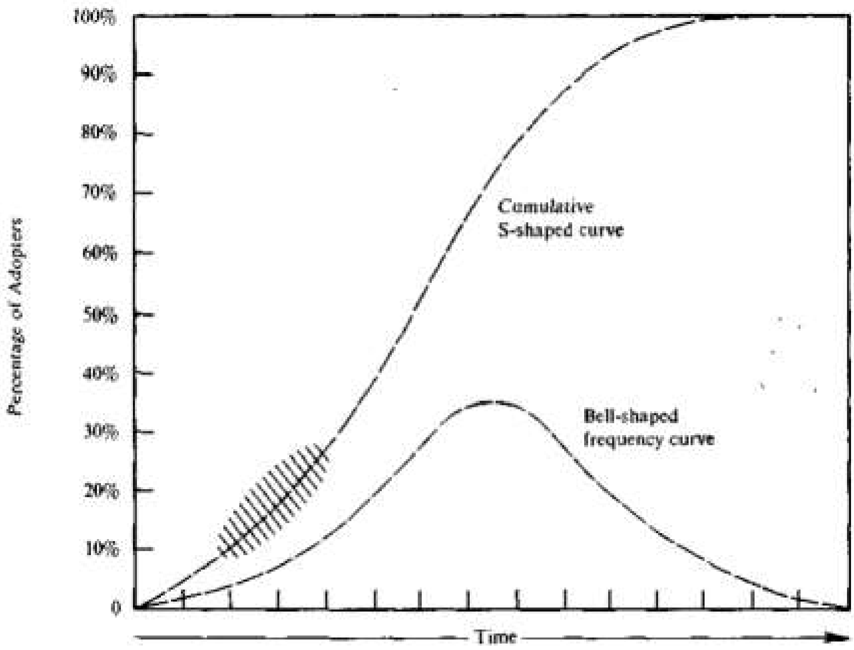


Figure 7. Adopter distribution curves (Rogers, 1962).

In Figure 7 the shaded area on the left identifies the core of the diffusion process, that is between about 10% and 25% of adopters. If a product survives this phase, it is unlikely that its diffusion will be stopped.

Rogers identifies customer segments based on their time of adoption.

If a new adopter convinces two peers to embrace the new technology and they do the same, the resulting distribution follows a binomial expansion, the function of which follows a normal shape.

Two key parameters to be considered to divide adopters into categories: the mean value of the sample $\overline{x}$, and the standard deviation, sd. Sd represents the dispersion with respect to $\overline{x}$.

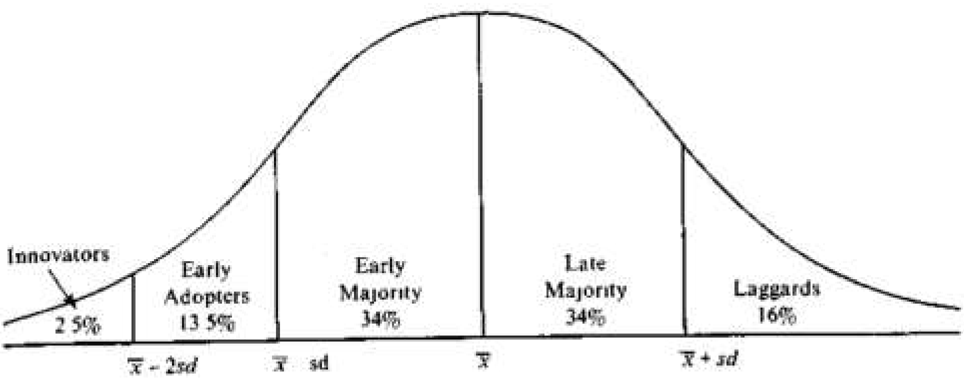


Figure 8. Adopter categorization on the basis of innovativeness (Rogers, 1962).

The resulting categories can be distinguished as follows.

Innovators:

They represent about 2.5% of total adopters, and they are the first to adopt new technologies. They are located on the diffusion curve on the left of $\overline{x}$-2sd. They are venturesome people willing to try new products and technologies. Innovators usually are cosmopolites and control appreciable financial resources, allowing them to bear the risk of failure and to absorb and apply technical knowledge needed to use new technologies.

Early adopters:

Between $\overline{x}$-2sd and $\overline{x}$-sd early adopters can be found. They represent about 13.5% of total adopters, and they enjoy the highest level of opinion leadership. In fact, other potential adopters get inspiration from the behavior of early adopters about the purchase of new technologies. Early adopters need to make risky but also weighted decisions when adopting new technologies in order to keep the credibility they are recognized for in the society.

Early majority:

Early majority's portion is right before $\overline{x}$. They represent 34% of total adopters. Early majority adopt new technologies driven by personal will, but they have weak leadership power.

Late majority:

Late majority adopter percentage is specular to the early majority's with respect to the mean value of the sample. They usually have scarce resources. Therefore, they embrace new technologies only when the risk of failure is negligible and economic necessity and network pressures arise. Diffusion of innovation is not affected by the behavior of late majority, because system norms start to influence it before late majority is convinced.

Laggards:

They represent the remaining 16% of the adopters. Their reference is the past, in terms of values and technologies. So, when they adopt a technology, probably it has already been overcome by a more recent one. They have almost no opinion leadership.

Moore adds that an innovative product needs to change its features along its diffusion depending on the target adopter category. He introduced the concept of "*Crossing the chasm*": if a product survives the early adopters' market diffusion phase, it needs to change in order to meet the requirements of the early majority category. Early majority adopts a new product only if it is sufficiently reliable in terms of capability to fully satisfy their needs.

He identifies some phases of the market life with peculiar characteristics:

- *Early market*: "Every truly innovative high-tech product starts out [..] with no known market value or purpose but with 'great properties' that generate a lot of enthusiasm within an 'in crowd'". It causes "an initial blip" in sales "and not the first indications of an emerging mainstream market" (Moore, 2001). On the adopter curve, it comprises the innovators' and the early adopters' segments.

- *Bowling alley*: effect of a "'bowling pin' strategy, where one targets a given segment not just because one can 'knock it over' but because, in so doing, it will help knock over the next target segment, and thus lead to market expansion" (Moore, 2001). The first portion of the early majority segment is characterized by such effect.
- *Tornado*: "A mass-market phase of the Technology Adoption Life Cycle that follows the bowling alley" (Moore, 2001), where sales ramp up franticly.
- *Main street*: the mainstream market, corresponding to late majority adopters.
- *End of life*: it corresponds the laggard adopters.

1.7 Dominant designs and Abernathy & Utterback model

Key definitions:

I. *Dominant design:*
"A single configuration or a narrow range of configurations that account for over 50 percent of new product sales or new process installations and maintain a 50-percent market share for at least four years" (Anderson & Tushman, 1990). Regardless the specific parameters considered to define a design as dominant, the crucial feature is that it establishes itself as an undisputed master on its market in terms of adoption.

For Anderson and Tushman dominant designs allow many benefits to the firm: focus on the optimization of organizational processes for volume and efficiency, more stable relations with suppliers and customers, and lower production costs and product price.

If a dominant design becomes an industry standard, modularity increases.

Abernathy and Utterback propose that the emergence of a dominant design allows producers to gradually shift the focus of their effort from product innovation to process innovation due to the succession of three phases.

Uncoordinated phase (performance maximization):

"Early in the life of process and product, market expansion and redefinition result in frequent competitive improvements. The rates of product and process changes are high and there is great product diversity among competitors" (Abernathy, Utterback, 1975).

Segmental phase (sales maximization):

"As an industry and its product group mature, price competition becomes more intense. Production systems, designed increasingly for efficiency, become mechanistic and rigid. Tasks become more specialized and are subjected to more formal operating controls. In terms of process, the production system tends to become elaborated and tightly integrated through automation and process control. […] Such extensive development cannot occur however until a product group is mature enough to have sufficient sales volume and at least a few stable product designs" (Abernathy, Utterback, 1975).

Systemic phase (cost minimization):

"As a process becomes more highly developed and integrated and as investment in it becomes large, selective improvement of process elements becomes increasingly more difficult. The process becomes so well integrated that changes become very costly, because even a minor change may require changes in other elements of the process and in the product design." (Abernathy, Utterback, 1975).

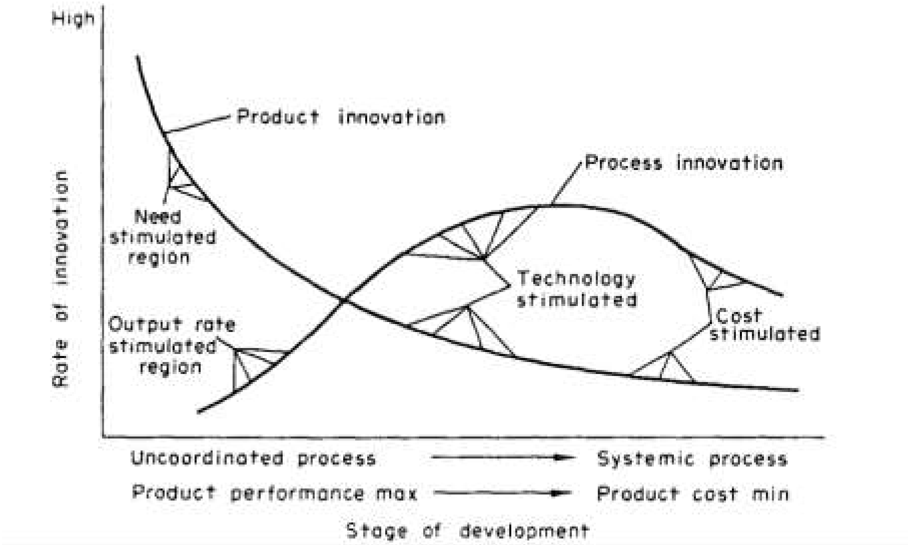


Figure 9. Innovation and stage of development (Abernathy, Utterback, 1975).

Suarez and Utterback analyzed the variation in the number of firms along time for specific technologies. As in the example shown in Figure 10, when a technology emerges the total number of actors follow an inverted U-Shaped curve.

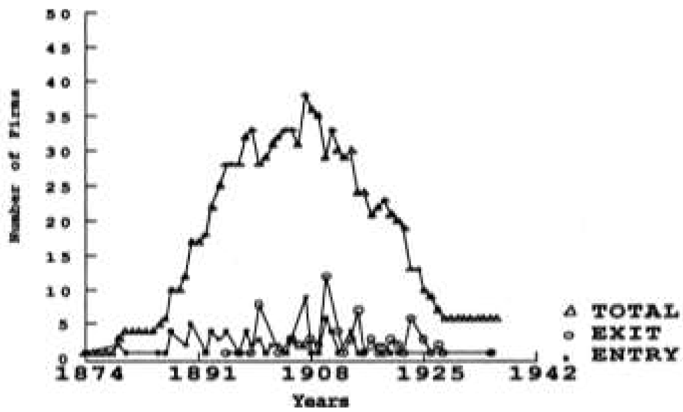


Figure 10. Number of Firms Participating in the Typewriter Industry in the U.S. (Suarez, Utterback, 1991).

Abernathy & Utterback model.

A general overview of the concepts introduced till now can be organically obtained through the Abernathy & Utterback model, that has been improved and extended also by other authors.

Let us consider the performance S-curve, the bell-shaped frequency curve for adopters, the rate of innovation curves, and the number of firms curve together. A relationship can be identified among them, as in Figure 11.

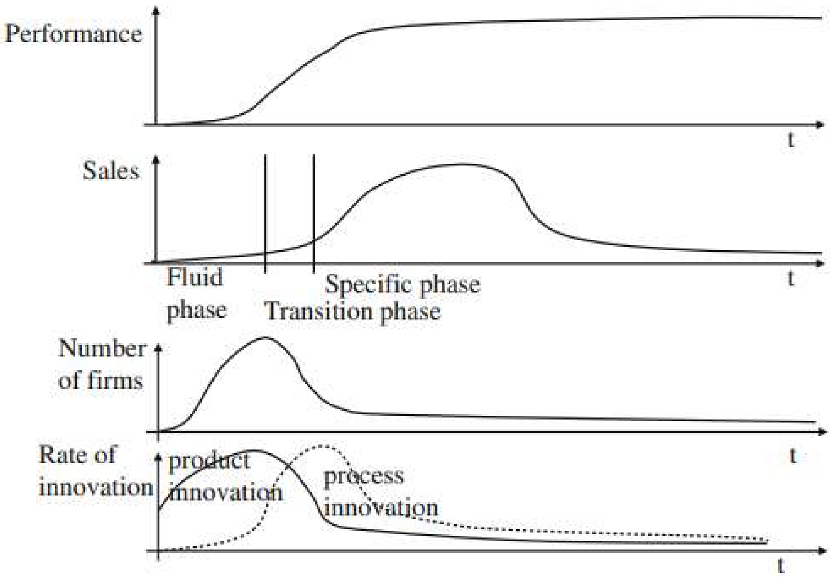


Figure 11. The Abernathy and Utterback's model (Cantamessa, Montagna, 2016).

The overall TLC can be divided into three main phases: fluid phase, transition phase, and specific phase.

Fluid phase:

Performance struggles to increase despite a high rate of product innovation because the new technology is still immature and technical barriers need to be overcome. For those reasons sales are still poor. At the same time the number of firms is rapidly increasing due to opportunities opened by the new technology and the perspective of being an early player in a new market. According to Abernathy and Utterback product innovation is at its prime seeking the best design in terms of pure performance.

Transition phase:

Performance sharply increases, a dominant design is defined. Sales curve sees its first inflection and grows rapidly. Thus, the number of firms sees a first shakeout due to technological reasons. Now R&D can focus more on process innovation, rather than on product innovation.

Specific phase:

Once the technology is mature and well-established in the market, a continuous exploitation of it allows to gradually reach its limit. Meanwhile sales reach the apex of the bell-shaped curve and start to decrease. A second shakeout of the number of firms occurs due to managerial reasons, along a path leading to oligopoly.

In a nutshell, the general pattern followed by the Abernathy and Utterback model is:

- Product innovation leads to a dominant design;
- Innovation effort can now focus on process innovation, that leads to economies of scale;
- Exploitation of economies of scale allows to reach the minimum efficient scale (MES);
- The achievement of MES and oligopolies are mutually dependent. For example, in the actual car industry firms are merging or they are creating joint ventures to reach MES, thus moving towards an oligopoly; at the same time, only an oligopolistic environment offers the conditions to reach MES.

Anderson and Tushman suggest that a dominant design will occur before the peak of the frequency curve, and its emergence enables sales to take off; at the same time, they reject the idea that the decline of sales is due to the emergence of a dominant design. If a dominant design emerged after sales peak, it would benefit high sales among late adopters only and it would be the consequence of their tendency to focus on cost and select a commodity version of the technology.

2. Technology forecasting models

2.1 Factors affecting forecasting

According to Martino (1993) three main categories of factors can affect forecasting.

Environmental factors.

- Technological factors: in particular, attention should be paid on early stages of innovation, developments in other fields, technological changes along the value chain, and accuracy of starting data.
- Economic.
- Managerial: mainly, impact of changes in managerial technology.
- Political.
- Social.
- Cultural: changes in the set of values supported by society.
- Religious-ethical.
- Ecological: expected growing impact of such factor on innovation.

Forecaster's biases.

- Vested interest.
- Narrow focus on a single technology or technical approach.
- Commitment to a previous position on the same topic.
- Overcompensation: the forecaster overcompensates one of the other biases.
- Excessive weight attributed to recent evidence and/or on troubles of the recent past.
- Unpleasant course of action required by the forecast.
- Dislike of the source of an innovation.
- Systematic shift from optimism to pessimism as the length of the forecast increases.

Core assumptions.

Regardless the degree of fit of the model to data, results are mainly affected by the core assumptions made at the early stages of the analysis.

The impact of all those factors on forecasting results needs to be mitigated as much as possible, and a possible solution is to structure the algorithm of analysis such that it can channel them inside it. The attempt to achieve that goal will be explained in detail in Paragraph 2.3.

2.2 Some current forecasting models

Since the focus of the analysis is on the Fluid Phase, defined as by Abernathy and Utterback, the following forecasting models will be described with focus on that phase only.

2.2.1 Technology forecasting

The Fluid phase can be effectively described by the following formula representing a logistic curve:

$$dv/dt = kv - bv^2$$

dv/dt represents an infinitesimal increment of a variable v with respect to an independent variable t (e. g. time, cumulated R&D investments, or cumulated industry revenues). Such increment is proportional to the performance kv reached by the technology at a given moment t_0, corrected by a quadratic saturation effect (bv^2). *k/b* represents the limit to which the performance curve asymptotically converges.

In the first portion of a performance curve the saturation effect is negligible, and an estimation of *k/b* is weak; therefore, the equation can be simplified into an exponential curve differential equation, and it can be written as:

$$dv/dt = kv$$

The solution of the differential equation is:

$$v(t) = \mathrm{v(t = 0)} * e^{(k(t-t0))}$$

v(t=0) is the value of *v* at time 0.

Such forecasting formula provides a reliable approximation of the first half of the S-curve.

For short-term forecasting, and in particular at the beginning and at the end of the S-curve an even more simplified approach can be considered: the linear approximation. The differential equation in that case is:

$$dv/dt = k$$

And its solution is:

$$v(t) = \mathrm{v(t = 0) + kt}$$

2.2.2 Customer Focused Technology Planning (CFTP)

"Customer Focused Technology Planning (CFTP) is a planning framework designed to help firms focus their technology investments to increase their return on technology investments." (Paap, 1996).

The goal is to add value to a company by focussing efforts on the aspects providing most of the value to customers. The latter can be obtained through a collection of information on customer needs, on technology availability, and on potential competitors.

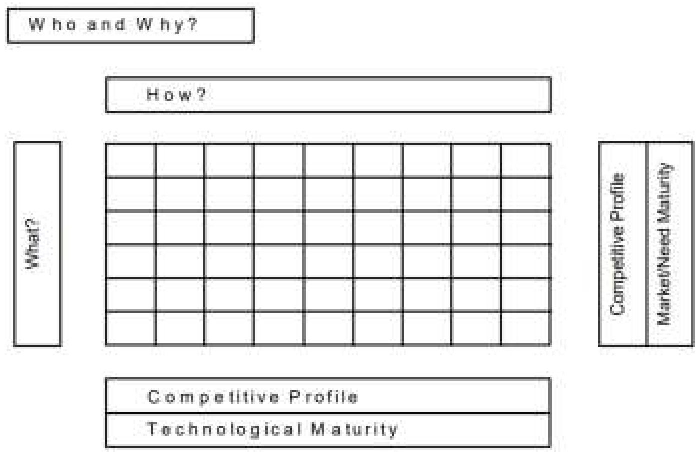


Figure 12. Generic CFTP map (Paap, 1996).

As shown in Figure 12 the CFTP map is usually similar to the House of Quality map in Quality Function Deployment, but while the former is about strategic R&D investment options, the latter is more about operations. Moreover, CFTP map offers more flexibility in tailoring it case specifically.

CFTP analysis usually involves many actors working on its development and forming cross-functional and cross-skilled teams. They aim at sharing information needed to develop a strategy.

CFTP analysis can be split into four main steps.

I. Market profile development.
It answers to the questions “Who are the customers and why are they important?”. It corresponds to the upper section of the CFTP map. Rows represent product classes, while columns market segments based on decision patterns.

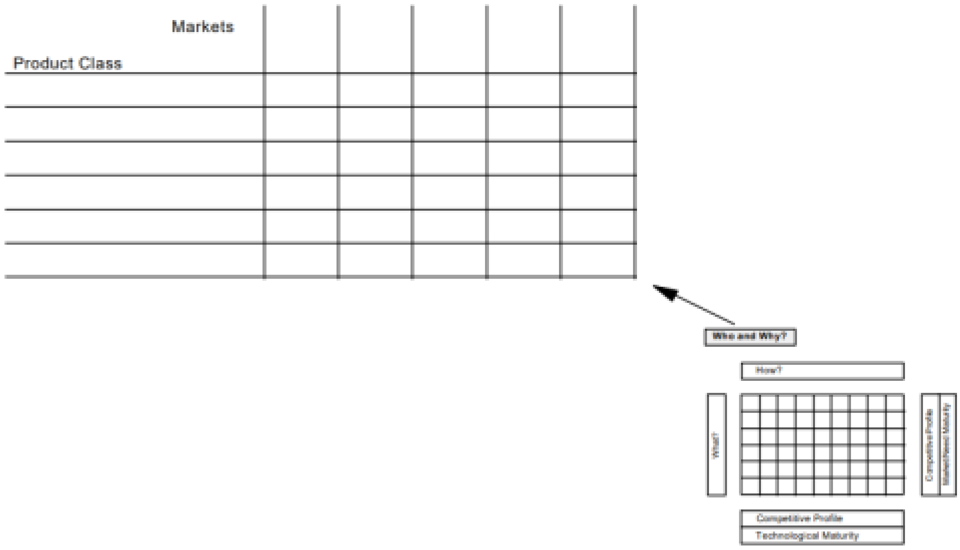


Figure 13. Generic CFTP product market map (Paap, 1996).

II. Technology-market interactions map for each considered market segment.
For each identified market segment, market requirements, technical characteristics, and competitive dynamics are analysed. Drivers of the choice done by customers and factors related to third parties influencing choices considered through the Performance Characteristics map.

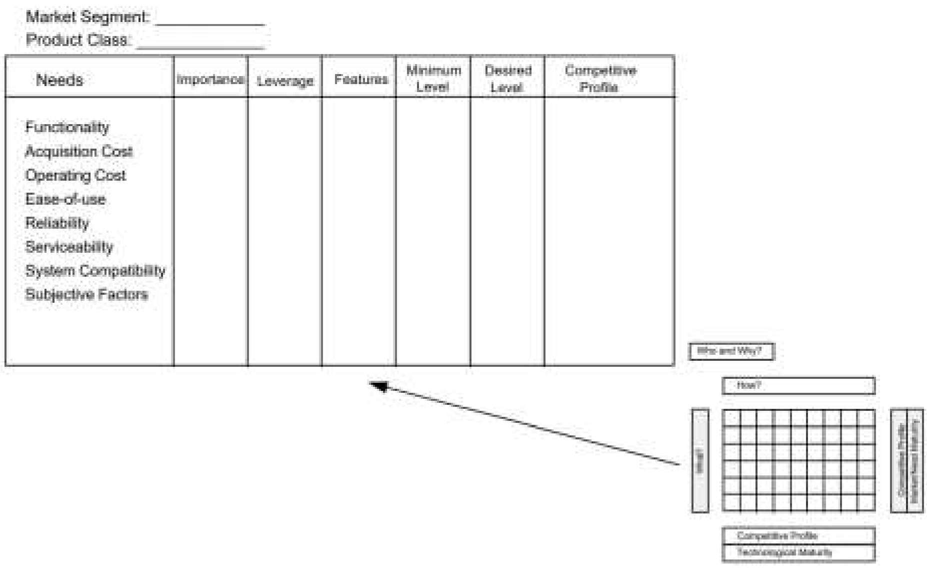


Figure 14. Generic Performance Characteristics Profile (Paap, 1996).

III. Technology investment opportunities identification.
Through a technology impact analysis some basic questions need to be answered:
- What performance characteristics drive the technology?
- When will the considered technology be mature?
- Where are we along the considered technology S-curve?
- Where is competition?
- What are the technical options and when willl they be available to mass market?

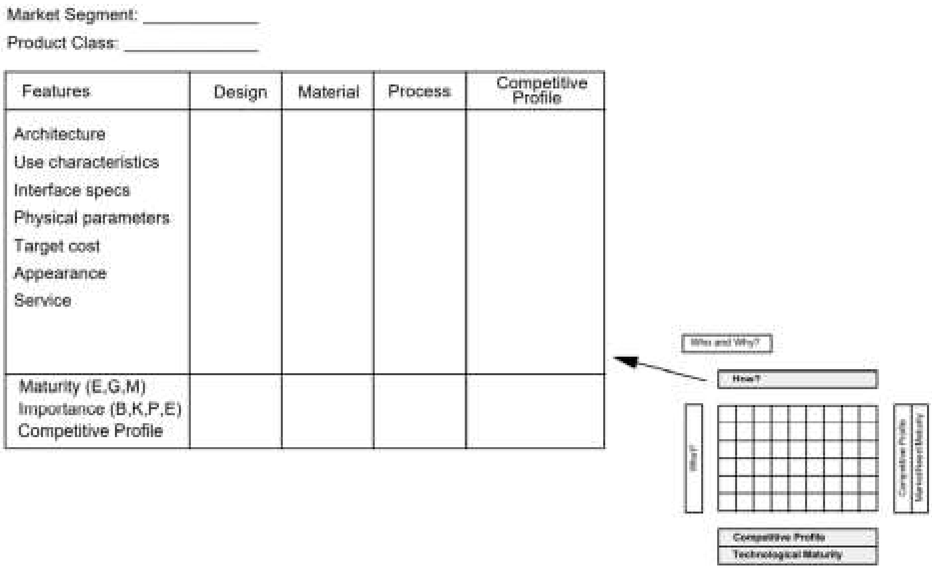


Figure 15. Generic Technology Impact Profile (Paap, 1996).

IV. Projects and priorities selection.
Once possible positive and negative interactions between performance characteristics and technology impact are checked, projects and investments direction can be selected with the aid of the CFTP map.

Performance Characteristic	Importance	Leverage	Ingredient Technologies				Process Technologies		Competitors		
			Sweetners	Fats and substitutes	Shelf life enhancers	Flavorings	Formulation	Mixing	CI	A	B
Flavor	1	M	+	++	+	++	+	+	3	2	1
Appearance	2	L	+	+	++	o	++	+	3	2	1
Fat Content	3	H	o	++	o	o	o	o	2	1	2
Texture/ Mouthfeel	4	H	+	++	+	++	+	+	2	1	3
Price	5	M	o	+	+	+	++	++	3	2	1
Calories	6	L	++	+	o	o	o	o	1	1	1
	Competitor Profile	Constar Inc.	●	⊙	⊙	○	○	⊙	10% share		
		A	⊙	●	●	●	⊙	●	30% share		
		B	⊙	⊙	●	●	●	⊙	40% share		
	Relative Maturity		G	E	G	G	M	G			

Importance: Rank order, **1** is most important
Leverage: **H** = high **M** = medium **L** = low (refers to customer reaction to performance improvements)
Technology Impact: **++** = technology influences greatly (positive or negative) **+** = moderate impact **o** = low impact
Competitors: **1** = best **2** = second best **3** = third best; ties indicate equal performance
Competitive profile: ● = strong capability/high investment ⊙ = moderate capability/investment ○ = low capability/investment
Relative maturity: **E** = Emerging technology **G** = Growing technology **M** = Mature technology

Figure 16. Example of CFTP Map (Paap, 1996).

In conclusion, CFTP is more focused on investments strategy rather than on pure R&D; anyway, thanks to its intrinsic adaptability it can be a useful tool to make more accurate guesses on future dominant designs of aircraft powerplants.

2.3 Proposed forecasting model

Let us consider the Abernathy and Utterback model. If a technology is diffused enough, a huge amount of data can be collected, and estimations can be made with a reasonable margin of error.

If the focus is on the Fluid Phase, such amount of data is more limited, and estimations show a wider range of values. To partially overcome such uncertainty, the proposed forecasting model follows a three-phase approach, where the results of a purely quantitative analysis based on real measurable data are adjusted and complemented by qualitative and semi-quantitative considerations.

Moreover, the early stages of the proposed model aim at increasing awareness on technical criticalities specific to the scope of the analysis, thus reducing the risk of neglecting remarkable elements affecting the forecast.

The model is mainly based on Technology Forecasting and CFTP techniques.

2.3.1 Qualitative analysis

I. Market profile development.
A general overview of product classes and on reference markets can be achieved by the Product Market Map described in Paragraph 2.2.2.

II. Focal technologies in detail.
The technologies referred to the topic of the case study - aircraft powerplants - will be introduced from a technical point of view by a solution tree. It is a tree that starting from the top (Level 0) shows branches connected by *and* and *or* nodes. The solution tree will allow to get an overview of the competing technologies, and of the variants belonging to each of them.

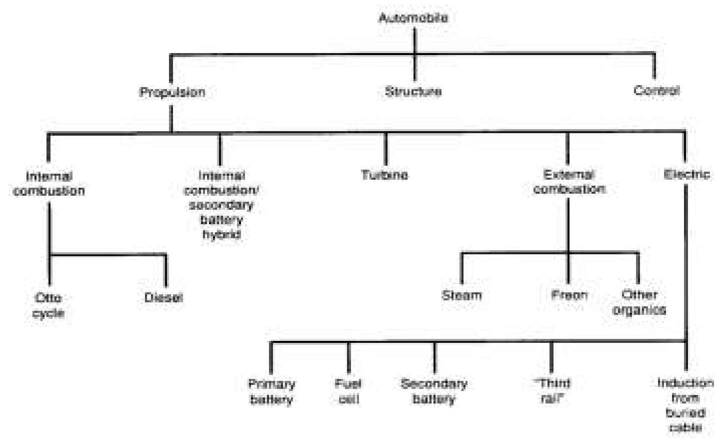


Figure 17. Solution tree (Martino, 1993).

After that, for each technology a block diagram will be developed to highlight the main architectural components and their mutual relationships, in order to evaluate the degree of architectural complexity and its implications.

III. Complementary assets evaluation.
A qualitative overview of the existing assets that could support future technologies will be performed.

2.3.2 Semi-quantitative analysis

I. Lead-Lag correlation.
Starting from the crucial technical aspects, the main correlations between the functional capabilities of each technology and any other valuable surrounding technology will be considered. For example, the state of the art of battery technology will be discussed, because it is at the core of any possible development of electric aircraft powerplant systems. This will provide information on the expected chronological offset of the performance curve of the core technology with respect to improvements of its related powerplant technology.

II. Technology-market interactions matrix.
The step "Technology-market interactions map for each considered market segment" of the CFTP analysis will be adapted to provide hints on the needs of customers belonging to the highest-interest market segment.

III. Technology impact map.
Step based on the CFTP "Technology investment opportunities identification" section. Ingredient and process technologies contributing to each powerplant technology will be evaluated in terms of capability to answer market needs and of maturity degree.

2.3.3 Quantitative analysis

The quantitative analysis will focus on the estimation of performance curves by considering real available data.

Performance curves.

The forecasted performance curves will be plotted according to the following steps:

1) Development of a performance indicator.
   A performance indicator will be developed based on some criteria:
   a) Parameters with overriding importance such that their absence is unacceptable from a performance perspective must multiply the other factors.
   b) Non-overriding parameters that imply mutual trade-offs must be added together.

c) Non-overriding parameters that do not imply trade-offs represent optional features, so they enter the scoring model in the form of *(1 + aA)*, where *a* is a coefficient and *A* the value of such parameter.

Let us call *x* and *y* the two parameters that concur in the evaluation of a performance indicator, whose value is equal to *x * y*; *x* and *y* need to be rescaled and weighted before computing the performance indicator:

a) Values of *x* of every technological variant are grouped, and their average and standard deviation are computed.
b) For every technological variant, such average is subtracted to its corresponding value of *x*.
c) For every technological variant, the result of point *b* is divided by the standard deviation; now, the values of *x* of every technological variant are centered on 0.
d) Values of point *c* are multiplied by 2.5 and added to 6, so that they all lie in the range from 0 to 10.
e) Results of point *d* are elevated by a factor, in order to weight appropriately *x* values with respect to *y* values.
f) Points *a* to *e* are iterated for the values of *y*.
g) Now, the performance indicator is equal to *x * y*.

Technological variants	Parameter x					Parameter y					**Performance indicator**
	Value	Parameter - Average	(Parameter - Average) / Standard deviation	Rescaled parameter	Weighted rescaled parameter (w. f. = 3)	Value	Parameter - Average	(Parameter - Average) / Standard deviation	Rescaled parameter	Weighted rescaled parameter (w. f. = 2)	
t1	1,00	-3,00	-1,39	2,53	16,16	2000,00	750,00	1,39	9,47	89,72	**1449,73**
t2	2,00	-2,00	-0,93	3,69	50,06	1750,00	500,00	0,93	8,31	69,13	**3460,58**
t3	3,00	-1,00	-0,46	4,84	113,57	1500,00	250,00	0,46	7,16	51,23	**5817,88**
t4	4,00	0,00	0,00	6,00	216,00	1250,00	0,00	0,00	6,00	36,00	**7776,00**
t1	5,00	1,00	0,46	7,16	366,64	1000,00	-250,00	-0,46	4,84	23,45	**8598,50**
t2	6,00	2,00	0,93	8,31	574,80	750,00	-500,00	-0,93	3,69	13,58	**7807,24**
t3	7,00	3,00	1,39	9,47	849,77	500,00	-750,00	-1,39	2,53	6,39	**5431,44**
Average	4,00					1250,00					
Standard deviation	2,16					540,06					
Weighting factor (w. f.)	3,00					2,00					
Rescaling factors:											
Multiplier	2,5										
Addition	6										

Table 6. Example of rescaled and weighted parameter *x*.

2) Evaluation of performance trends of each technology, through the exponential growth model of Technology Forecasting.

3) Evaluation future developments through a sensitivity analysis by diversifying growth rates of each technology.

Rate of innovation curves.

To better understand industry effort on a technology and to support performance curves estimation, rate of innovation curves will be plotted.

According to the Abernathy and Utterback model, the innovation rate curve is the sum of the rate of product and process innovation curves.

During the Fluid Phase efforts are mostly focused on product innovation. The rate of process innovation is negligible. Therefore, its estimation will not be taken into account.

The rate of innovation will be based on patents trends up to now.

2.3.4 Results refinement

The technological paradigm pivoting around the forecasted winning technology will be described.

The goal is to achieve a detailed overview by giving more emphasis on case-specific aspects that might be disregarded otherwise.

3. Case study

3.1 Boundaries and simplifications

The scope of the case study is powerplants applied on fixed wing aircraft, and in particular it aims at the identification of the potential dominant design in 2040.

It will focus on current and potential future technologies for both the power generation side and the propulsion side (i. e., the part providing energy transfer between the powerplant and the outside environment). Since powerplant architecture is basically integral, and the same components often contribute to power generation and to propulsion at the same time, evaluations will consider the whole powerplant as one.

Some boundaries limiting the analysis scope need to be set to avoid dispersion and inconsistent comparisons among technologies, thus they will be discussed in this paragraph.

The analysis will involve civil applications, while military aircraft powerplants will be excluded.

Based on the typology of operations, civil aviation activities can be divided into commercial air transport services and general aviation (non-commercial business aviation and aerial work).

The case study will focus on commercial air transport aviation. Inside it, five categories can be distinguished.

Aircraft category	Definition	Examples of aircraft types
Twin-aisle jets	Large jet-powered aircraft for medium and long-range operations	Airbus A330; A340; A350; A380; Boeing 747; 757; 767; 777; 787
Single-aisle jets	Jet-powered aircraft intended for short to medium-range operations	Airbus A220; A319; A320; A321; Boeing 737-700; 737-800; 737-900
Regional jets	Jet-powered aircraft intended for short-range operations	Bombardier RJ700; RJ900; Embraer EMB145; ERJ-170; ERJ-190
Turboprops	Turboprop-powered aircraft (does not include small general aviation aircraft)	ATR 42; ATR 72; Bombardier DHC-8
Business jets	Small jet-powered aircraft with a seating capacity of 19 or less	Beech 400A; Cessna 525/650/750; Falcon 2000; Gulfstream 450/550

Table 7. Description of aircraft categories considered in the analysis (Easa).

Twin-aisle jets are also called widebodies, while single-aisle jets are also called narrowbodies.

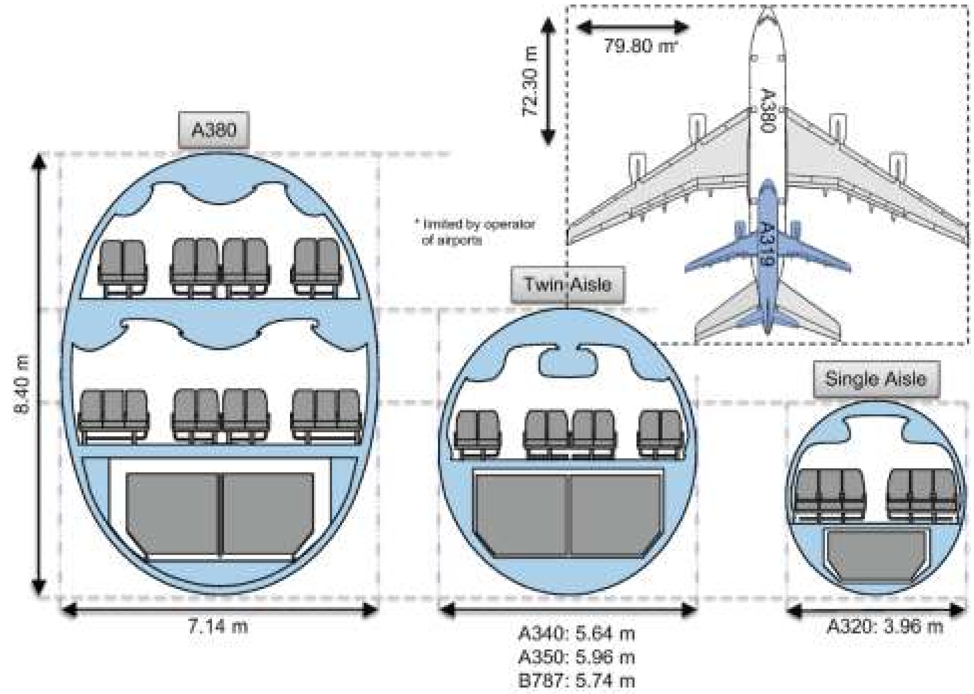


Figure 18. Fuselage cross section and size comparison of small single-aisle (A320), twin-aisle (A340, A350, B787) and double-deck twin-aisle (A380) aircraft (Breuer, 2016).

As anticipated, a powerplant system is made of a power generation section, and a propulsion section.

About the former, aircrafts of each weight class show different kinds of engine, all of them related to two main current technologies: internal combustion engine technology and jet technology.

About the latter, aircraft powerplants can be distinguished into ducted fan/propeller if there is a duct surrounding it, and unducted fan/propeller if there is not.

Internal combustion engine technology covers almost exclusively general aviation aircrafts; therefore, it will not be considered in the analysis.

Jet technology shows seven main derivatives: turbojets, turbofans, turboprops, turboshafts, propfans, scramjets, and ramjets.

Turbojets were the original technological variant, that due to performance and fuel consumption limitations were gradually substituted by turbofans and turboprops on fixed-wing aircrafts. Turbojets are now applied almost uniquely on cruise missiles and unmanned aerial vehicles.

Turboshafts are developed primarily as power generation source for rotary wing aircrafts (e.g., helicopters), as backup power source on large aircrafts (such as the auxiliary power unit or APU installed on airliners), and for some terrestrial and naval applications. For those reasons, turboshafts will not be considered as air transport aviation technological variant, but they are one of the key architectural components of the serial hybrid technology, as described in paragraph “Focal technologies in detail” (3.2).

Propfans represent a technological variant that was developed in the 1980s, but, due to some technological limitations at that time, development was stopped and only since a few years it has been seen as a new possible future high diffusion technology. Propfans will be discussed more in detail in the following paragraphs.

Ramjets and scramjets are uniquely used in small-scale military applications, and there is no market nor expected civil application for them up to now; therefore, they will not be taken in consideration.

Due to their diffusion, turbofans and turboprops will be considered as the reference variants of jet technology in air transport aviation.

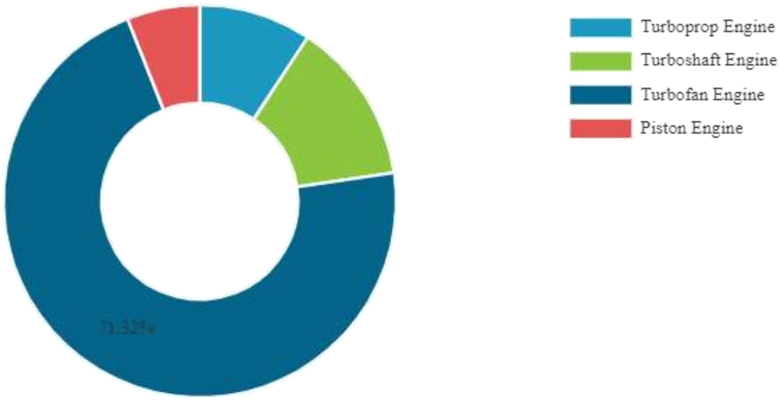


Figure 19. Global aircraft engine market share, by engine type, 2019 (Fortune Business insights).

Two very important simplifications need to be highlighted.

Changes in engine technology can affect airframe technology and architecture, leading to changes in the overall aircraft performance evaluation; that might bring the industry to follow different trends with respect to the ones predicted through a forecast on aircraft powerplant only. For example, a new engine technology might bring aerodynamic or structural implications that lead to a different design of the airframe, and the overall aircraft performance evaluation could diverge from the evaluation of powerplant performance only. Such effect will be neglected.

Some new potential substitutes may lack the needed redundancy in case of failure of one if their key architectural components. The compensation to that requires added weight and cost. That redundancy constraint will not be considered for simplicity.

3.2 Qualitative analysis

Market profile development

Aircraft categories in Table 7 are needed to perform the market profile development explained in Paragraph 2.2.2.

Definitions about customer needs that can be satisfied by a product are described on the rows of Table 8.

Market segments are on the columns of Table 8.

Depending on typology of operations, powerplants need to provide different kinds of performance which are reflected in different kinds of product classes, as shown in Table 8.

		Market segments			
	Product classes	Operators interested in STOL performance and short-range operations	Operators interested in short to medium-range operations and low payload capacity	Operators interested in long-range operations and high payload capacity	Operators interested in VIP transport operations
AS IS	Turboprop	x			
	Turbofan	x	x	x	x
TO BE	Propfan	x	x	x	x
	SAF Turbofan	x	x	x	x

Table 8. Product market map.

Every Product class corresponds to a current or an under-development variant of the current dominant technology, the Jet technology.

Each product class is defined on the basis of the technological variants of jet technology, by considering both current variants and future expected variants.

Original turbojets are no more considered as an "as-is" technological variant in the commercial air transport world, due to their poorer fuel consumption and pollution levels with respect to their derivatives. They are still applied only on old-generation fighter jets, and on cruise missiles, that lie outside the scope of the analysis.

The current technological variants available for fixed-wing aircrafts are Turbofans and Turboprops.

As is shown on Table 8, turbofans cover every market segment. Despite worse propulsive efficiency at low subsonic speed (roughly below 450 mph or 700 km/h) than turboprops, turbofans offer a much wider application range, covering every market segment. They perform better inside the typical cruise speed window between 600 and 650 mph, or 950 and 1050 km/h, and they are capable of higher service ceiling.

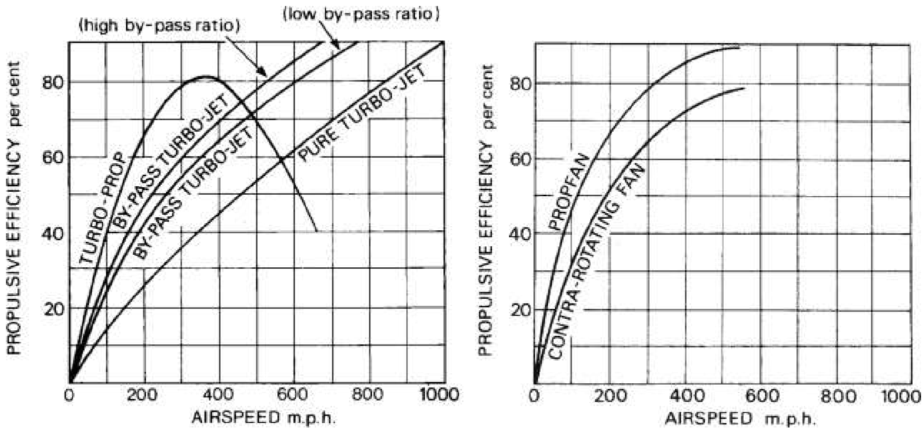


Figure 20. Propulsive efficiency comparison. *By-pass Turbojet* is a synonym of *Turbofan* (Hale, 2003).

Turboprops are more suited for aircrafts requiring good low-speed performance, in particular good short takeoff and landing (STOL) performance, and good climb rate at low altitude and speed; this is the reason why they represent a vertical market application for the homonymous aircraft category.

Figure 21 (left). An ATR 72-600 short-range aircraft with turboprop engines. (ATR aircraft)

Figure 22 (right). A Boeing 737 Max 8 with turbofan engines for short to medium-range operations (Reuters).

Figure 23 (left) A Boeing 777-300 ER with turbofan engines for long-range operations (Avionews).

Figure 24 (right) A Dessault Falcon 20 with turbofan engines for VIP tranport operations (Airliners).

Future technological variants under development are *Sustainable Aviation Fuel (SAF) Turbofan* and *Propfan* (also known as *Unducted Fan* or *UDF*).

The former is essentially a turbofan adapted to burn syntetic fuel, thus reducing emissions across the entire life cycle of fuel, from production to usage.

The latter is a different evolutionary approach of the turbofan technological variant.

SAF Turbofan and Propfan can be considered as an attempt to exploit a Sailing Ship Effect on the shoulders of Turbofans. They will be described more in detail in the second step of the Qualitative analysis from a technical point of view.

Markets are selected depending on customer decision patterns that lead them to the purchase of a specific product class.

The sale of aircraft powerplants is a business-to-business activity. Aircraft manufacturers usually select more than one engine type to equip each aircraft model, even though the current trend is to gradually shift to a single-engine type approach to better exploit performance maximization through a more refined integration between powerplant and airframe. Aircraft buyers are usually lessors or operators, and they select the engine type when ordering the aircraft if such option is available.

Market segments are identified on the basis of the activities performed by aircraft operators.

Operators interested in Short Takeoff and Landing (STOL) capabilities and short-range operations usually need aircrafts with good performance during transitional phases of flight. High cruise speed and high service ceiling are not a must-have.

Operators interested in short to medium-range operations are usually major carriers that need to feed their hubs for long-haul flights ("hub and spoke" network). They can also be low-cost carriers, that instead follow mainly a point-to-network approach. Even though the two business models are different, they can be considered as belonging to the same market segment from the perspective of customer needs related to aircraft powerplants. Low fuel consumption, short warm up and cool down time due to quick turnaround requirements, high powerplant commonality inside the fleet, and limited air and acoustic pollution are the main needs of such market segment.

Operators interested in long-range operations show powerplant-related needs that are similar to the previous market segment, but with some differences. First, they are usually major carriers that require the same constraints on fuel consumption, pollution, and fleet commonality; they also need well-performing powerplants at high speed and altitude, possibly with slightly higher cruise speed with respect to short to medium-range operations. Given the higher mass of such aircrafts, the thrust output required is much higher than narrowbodies'.

Operators interested in VIP transport need the capability to operate with speed and flexibility, both on ground and in the air. Since they usually have smaller and more diversified fleets, engine commonality is less important.

Finally, operators interested in freight operations represent a varied market segment, that traces most of the customer needs of the other categories inside it. Therefore, it is not considered as a market segment of its own.

All those market segments require improvements in emissions levels demanded by international regulations, by increased customer environmental awareness, and by operational limitations, such as noise abatement standards in the airport areas.

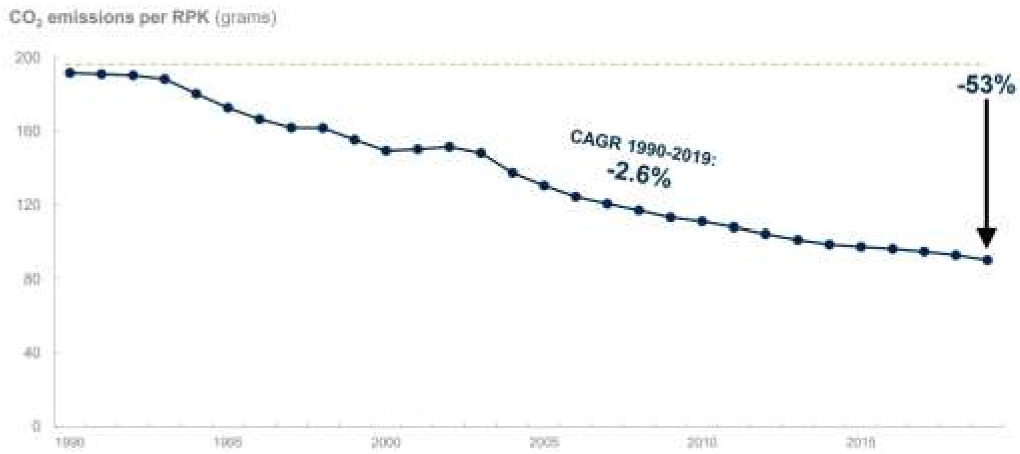


Figure 25. CO2 emissions per Revenue Passenger Kilometer (Airbus, 2021).

Focal technologies in detail

The following tree shows the main current and emerging technologies for air transport powerplants.

The alternatives are highlighted in green, in the form of a solution tree with *or* nodes.

Variants of each technology are in yellow, and the architectural components of each technological variant are marked in blue.

For the Jet technology, the list of components belonging to it follows the Air Transport Association codes 71-80 and 83.

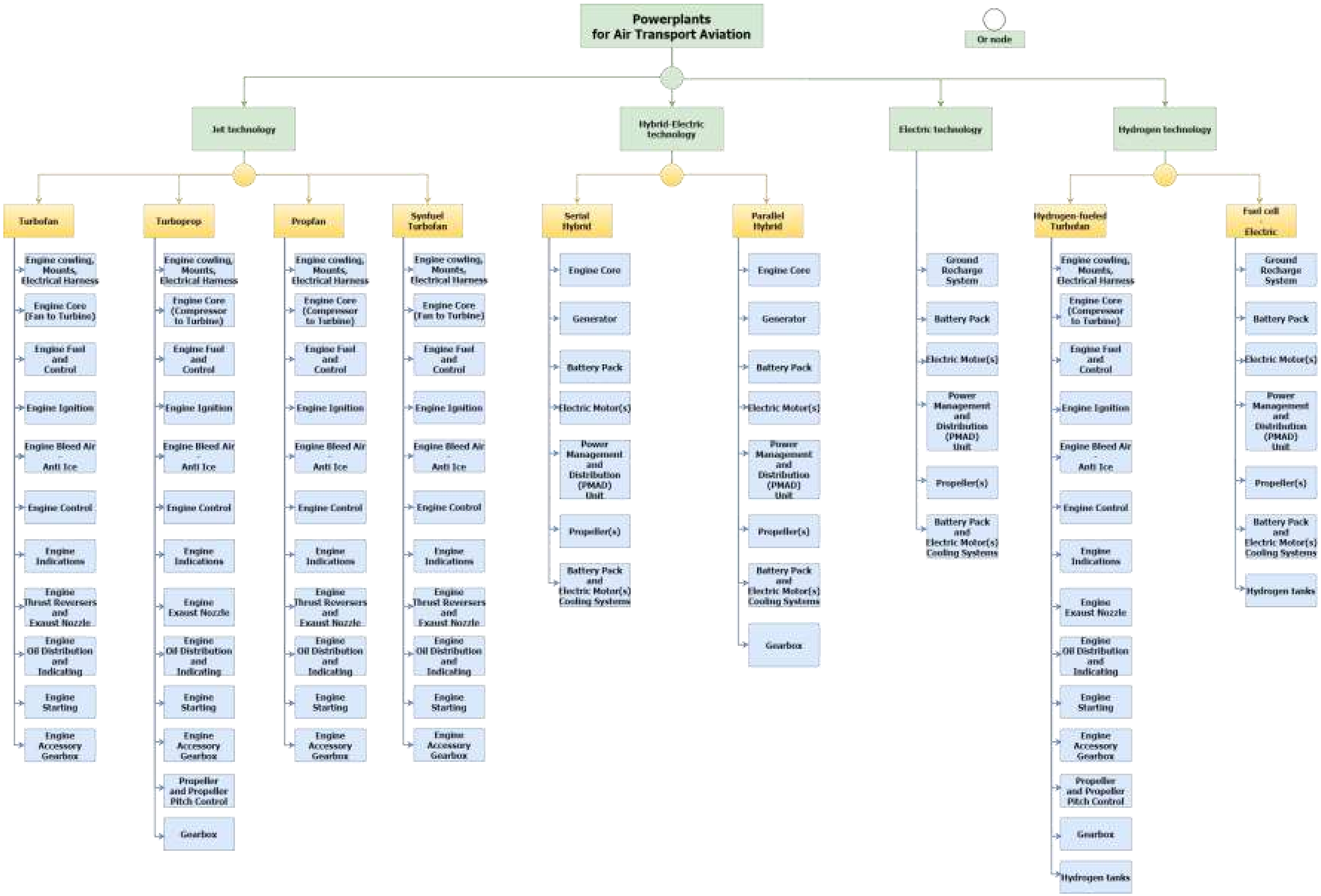


Figure 26. Solution diagram about powerplants for air transport aviation.

Every technological variant belonging to the Jet technology follows the same working principle of the original Turbojets: air coming from the engine intake is compressed through a set of compressor stages, then it goes into the combustion chamber where fuel is ignited; high-energy exaust gas flows through turbine stages, where thermal energy is partially converted into mechanical energy needed to drive compressor stages and a possible fan or propeller; exaust gas finally exits the engine core through a nozzle. Thrust is provided through the action-reaction principle linked to the high-speed exaust gas coming out from the engine core, and possibly by the fan or propeller driven the low-pressure turbine stages through a shaft.

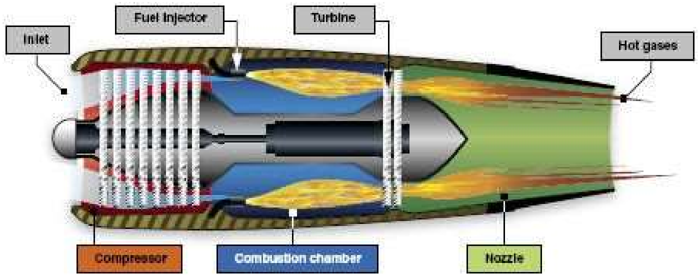
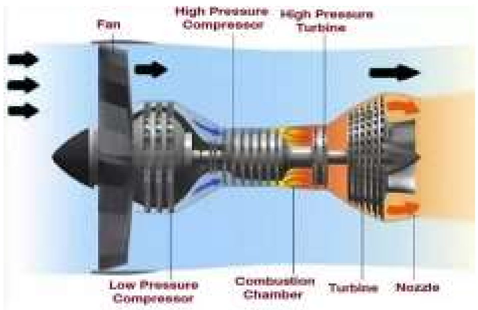


Figure 27. Turbojet breakdown (Aero-mechanic).

What distinguishes the original pure Turbojets from subsequent variants is that in Turbojets the entire airflow enters the engine core (the set of components from the compressor stages to the turbine stages), while in Turbofans and Turboprops most of the thrust is from the fan or the propeller, respectively.



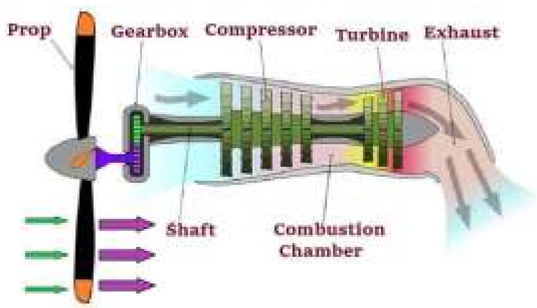


Figure 28. Turbofan (left) and of a turboprop (right) breakdown (Mechanicalboost).

A third current technological variant is Turboshafts, that, as anticipated, are not applied as main powerplant system on fixed-wing air transport aircrafts; therefore, it is not considered as current technological variant inside the analysis. Anyway, Turboshafts could probabily be applied on potential serial-hybrid powerplant systems. From an architectural point of view, a turboshaft is very similar to a turboprop. The main difference is that exhaust gas is expanded more to obtain higher mechanical power output, because such powerplant is inteded as power source, not as propulsion source.

Propfans are an evolution of Turbofans aiming at increasing fuel efficiency. Fan blades are no more covered by a fan duct, and they are coupled to the low-pressure turbine with no need of a shaft connecting them in most of the cases. Propfans development started betwen the 1960s and 1970s, but due to technological limits of that era and higher engine noise with respect to turbofans they were abandoned from 1980s until late 2000s.

Now, new propfan prototypes are under development and they are currently performing ground testing.

Synfuel Turbofans are even closer to current Turbofans from an architectural point of view.

Concurrent technologies that could substitute Turbojet variants are Hybrid-Electric technology, Battery Electric technology, and Hydrogen technology.

Hybrid electric powerplants show highly diversified variants, that can be summarized into Serial-Hybrid, and Parallel-Hybrid.

In a Serial-Hybrid configuration a conventional tail-mounted Turboshaft powerplant rotates a power generator; electrical energy is then managed by a Power Management and Distribution (PMAD) system, and spins one or more electric motors connected to fans or to propellers. A battery pack acts as an electric energy buffer and as a backup source in case of turboshaft failure.

In a Parallel-Hybrid configuration one or more jet engines run in parallel to electric engines powered by a battery pack. The purpose is to fly electric where low power demand is required, such as at cruise altitude; it is also to assist Turbofan or Turboprop engines when high thrust settings are required, for example during takeoff.

Figure 29. (Left) example of Serial-Hybrid powerplant (Greencarcongress); (right) example of Parallel-Hybrid powerplant (Aviationweek).

A purely Electric aircraft relies on batteries only as energy source, and electric motors spin propellers or fans.

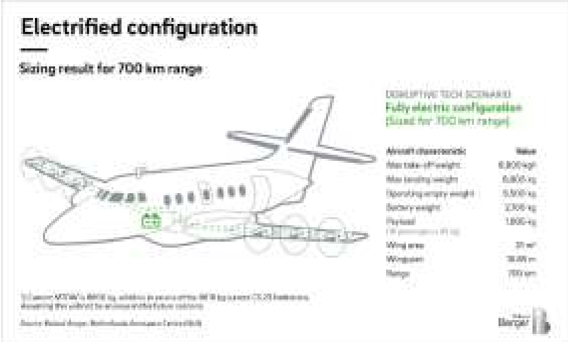


Figure 30. Example of a Battery Electric aircraft layout (Berger, 2021).

The last concurrent technology is the Hydrogen one. Two main derivatives will be considered: Hydrogen-fueled turbofans, and Fuel Cell-Electric powerplants.

From a technical point of view, the main challenge in Hydrogen management is storage, as it will be better explained in the Semiquantitative analysis.

Hydrogen-fueled turbofans burn Hydrogen instead of kerosene, and as in the case of Synfuel, technical modifications are required for such adaptation, but most of the engine layout and components remain untouched.

Fuel Cell-Electric powerplants are probably the most innovative technology, together with Electric technology. A Fuel Cell provide energy managed by a PMAD system to electric engines, that turn fans or propellers. As in the purely Electric case, a batery pack acts as buffer and backup energy source.

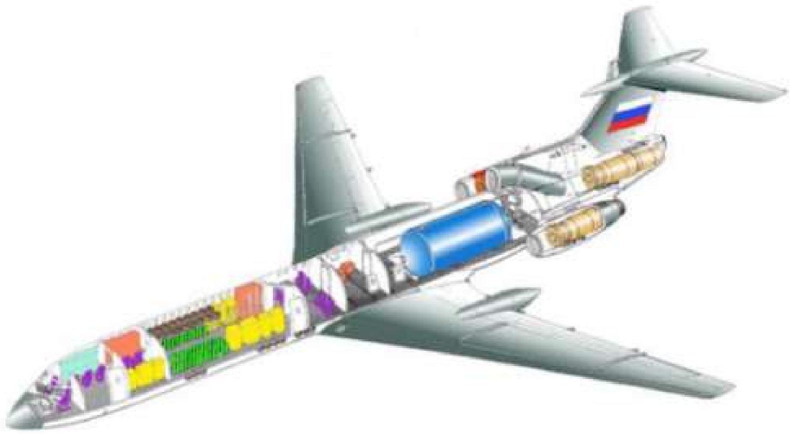


Figure 31. Tupolev 155 with Hydrogen-fueled starboard turbofan; Hydrogen tank in blue (Leeham News and Analysis).

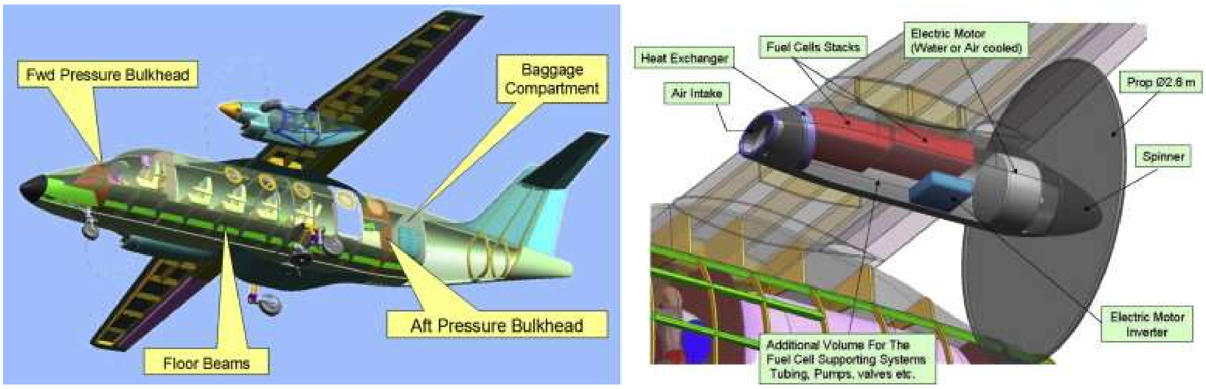


Figure 32. Layout of a Fuel Cell-Electric regional aircraft (Romeo et al, 2013).

By considering the key architectural components of each technology, block diagrams can be drawn in order to highlight the main architectural differences due to the potentially competing technologies.

Architecture level of complexity can heavily affect aircraft performance. Higher weight, lower reliability of the system, and higher maintenance cost are only some of the implications due to a complex architecture.

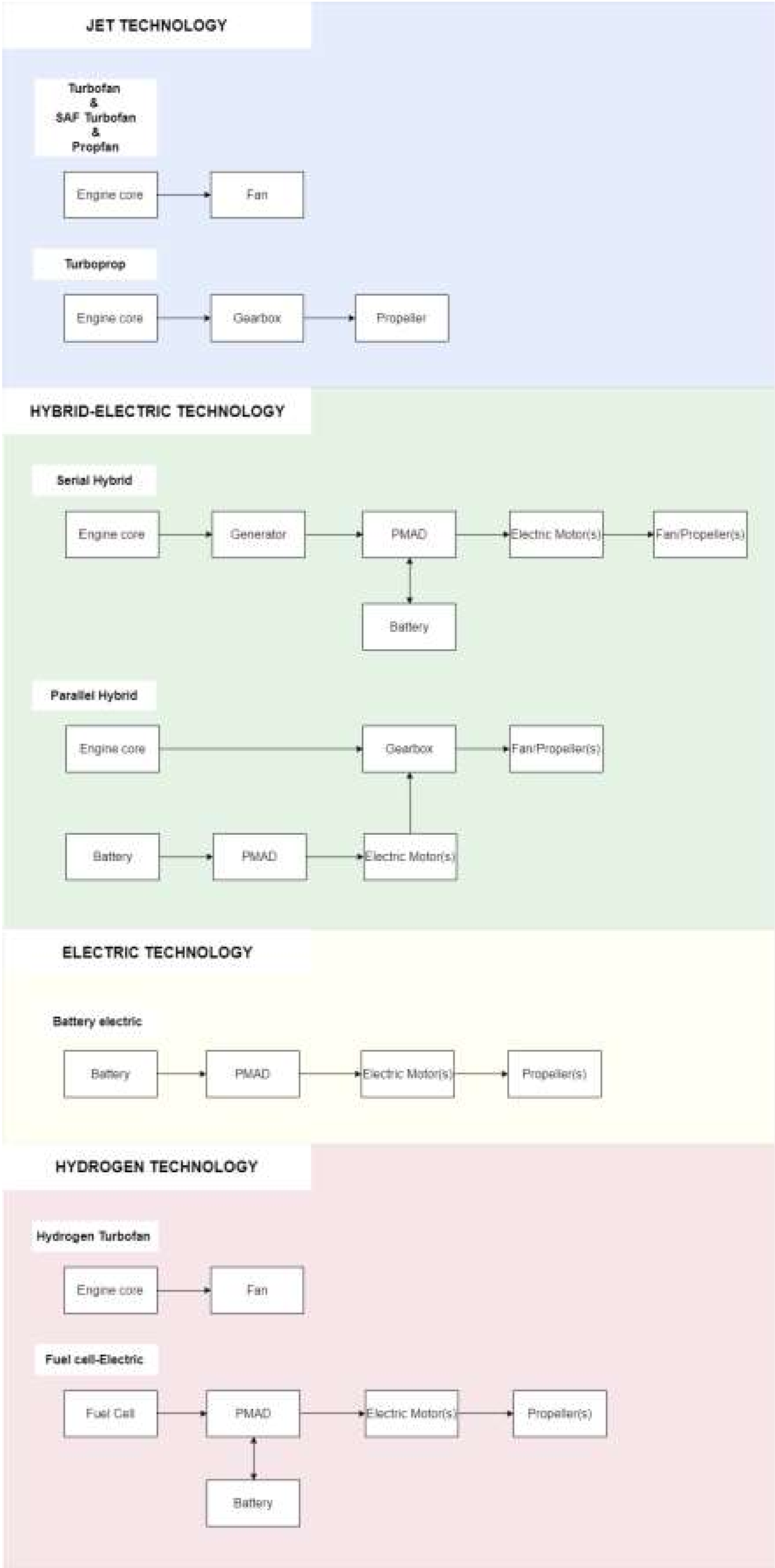


Figure 33. Block diagrams showing the key architecture components of each technology and its variants.

Complementary assets evaluation

Airport infrastructure for current kerosene-fueled jets, SAF jets, and propfans.

The main complementary asset to aircraft powerplants is the airport infrastructure, that, in turn, consists of two main systems: aircraft refueling infrastructure, and aircraft maintenance infrastructure.

Aircrafts equipped with current jet powerplants enjoy a well-established airport infrastructures.

Similarly, propfan and SAF powerplants can exploit the capabilities of current airport infrastructure because they all address to the same reference technology.

Fuel handling chain starts from a refinery providing kerosene as output product. Then, kerosene is transported to the airport through pipelines, or on tankers, on trains, or on trucks. It is stored in the airport fuel farm, and finally it is pumped inside aircraft fuel tanks through fuel hydrant systems or trucks.

Routine maintenance is usually performed in hangar, and for jet technology airport maintenance infrastructures are already fully effective.

Airport infrastructure does not require major changes in the case of SAF turbofans and propfans.

Airport infrastructure for battery electric aircrafts.

Electric aircraft powerplants require instead a completely new infrastructure.

Electric supply chain needs to be built or at least heavily upgraded. To provide a clue on the magnitude of electric energy required, an airport with 30 flights per day of propeller-driven aircrafts for short-range operations and up to 78 passengers needs between 18 MW and 21 MW per day of electric energy (Trainelli et al., 2019).

Electric supply chain consists of supply, storage, and distribution steps.

Recharge time has also to be considered, because typical turnaround time for short and medium-range aircrafts is between 20 and 30 minutes. Therefore, two recharge strategies are possible: battery swap, and plug-in recharge. Each of them shows pros and cons. Battery swap allows to perform recharge within the typical turnaround times for short and medium-range aircrafts. But at the same time, such strategy requires costly spare batteries. A plug-in strategy is much more time consuming, but it requires a smaller energy storage facility needed as buffer only, and no expensive spare batteries. However, congested airports and long-range aircrafts would require excessive amounts of energy to make a plug-in strategy feasible.

The amount of electric energy required should come not only from electric grid, but also from a solar panel system that exploits the undeveloped land around the airport (Zekun et al., 2020). That would increase investments and time to realize the infrastructure.

Airport infrastructure for Hydrogen-powered aircrafts.

As in the case of electric technology, airport infrastructure needs to be changed to serve Hydrogen technology.

Estimations suggest that with Hydrogen refueling time will be longer than current refueling times, with 5% to 10% of increased turnaround times.

Between 2035 and 2040 an early ramp-up phase of Hydrogen-fueled aircrafts will take place, according to FCH Europa.

Global airport demand of Hydrogen will be between 10 and 40 M Tons per year.

Hydrogen can be mainly produced through electrolysis of water or through the combination of natural gas and carbon. The first technique is carbon-free, when renewable resources are exploited to produce electric energy; the second technique is carbon-neutral.

Compressed or liquid Hydrogen then reaches airports through pipelines or on trucks.

A storage facility is needed to contain the supply. Possibly it is stored in a liquid form to save volume.

Aircrafts can be finally refueled by trucks or by refueling stations.

3.3 Semi-quantitative analysis

Lead-Lag correlation

By looking at product architecture of each technology and through literature research, some technological bottlenecks can be found:

- Energy storage and recharge time for electric and Hydrogen technologies.
- Powerplant efficiency and CO2 emissions for applications based on Jet technology.
- Fuel cell technology for Hydrogen-electric technology.

Energy storage for Hydrogen technology.

For current turbofans and turboprops, fuel is stored in fuel tanks located inside the wings and in the middle part of the fuselage, thus saving fuselage volume for payload.

For electric technology instead, energy is stored in batteries located inside the fuselage.

For Hydrogen technology, Hydrogen can be stored in gaseous or liquid state inside appropriate tanks. Gaseous Hydrogen can be stored at ambient temperature and in moderately pressurized tanks, but for aerospace applications that is not feasible due to higher quantities required that would lead to excessive volume of the tanks; therefore, liquid Hydrogen needs to be stored at low temperature (-243 °C) and higher pressure to increase the volumetric and gravimetric capacity.

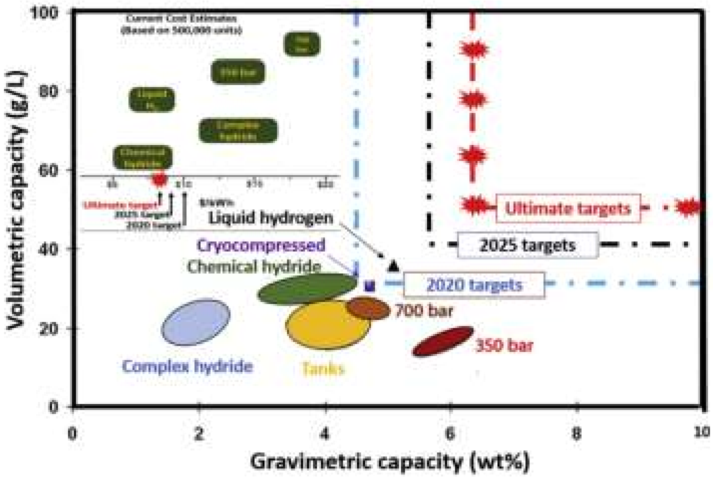


Figure 34. Hydrogen storage system trends with respect to US DOE targets (Boateng, Aicheng, 2020).

Both batteries and Hydrogen tanks installed inside the fuselage reduce payload volume.

Moreover, insulated and pressurized Hydrogen tanks increase aircraft empty weight with respect to current fuel tanks.

Energy storage for Electric technology.

Current battery technology is mainly pushed by the automotive industry, and battery performance in terms of Wh/kg is rapidly increasing. As shown in Figure 35, performance shows massive improvements during the last decade:

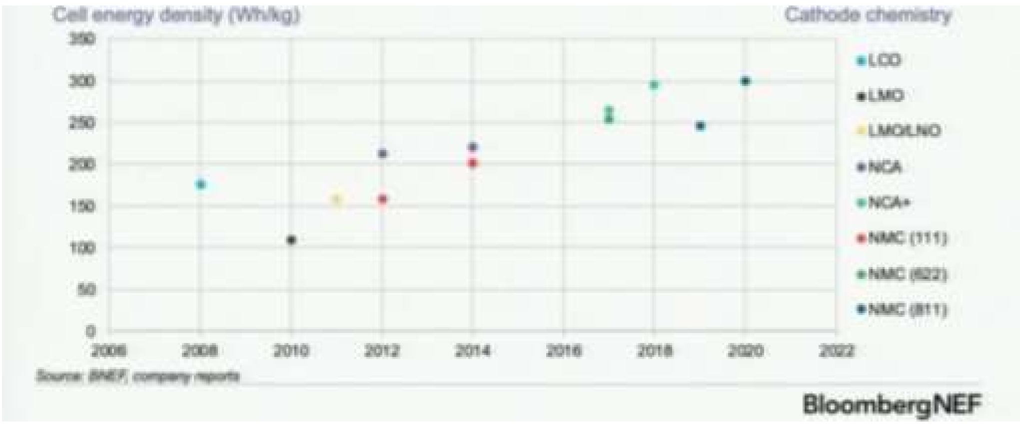


Figure 35. Battery Energy density trend (Field, 2020).

However, batteries developed for terrestrial applications require different safety characteristics with respect to aerospace applications. As suggested by Fehrm (2019), the closest battery technology to aerospace application is the one developed for Formula E. Formula E battery system actually provides 54 kWh/kg weighting 250 kg, for an energy density of 216 Wh/kg.

So, by looking at the trend of Figure 35, current battery performance expressed by its energy density is about two orders of magnitude lower than the fuel it could replace and the one it could face in the future: kerosene and Hydrogen, respectively. For a comparison, 1 kg of kerosene provides 11 900 Wh of energy, while Hydrogen 36 300 Wh.

Powerplant overall efficiency and CO2 emissions of current jet engines.

Current jet engines have seen a gradual increase in the overall efficiency across the years. Turbojets, the initial technological variant, suffered poor efficiency with respect to current high bypass ratio (BPR) Turbofans.

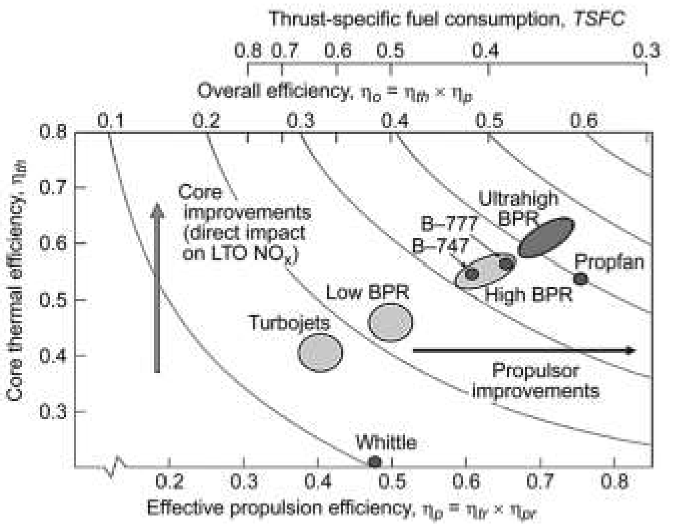


Figure 36. Overall efficiency of Jet technological variants (Suder K. L., Heidmann, 2017).

Next generation Turbofans will probably match the overall efficiency of Propfans that are actually under development. By 2040, overall efficiency is predicted to be between 50% and 55%.

However, such value is still much lower than powerplants equipped with Fuel cells or electric powerplants, that are around 65% and just below 100%, respectively.

A detailed numerical comparison will be provided in the Qualitative analysis section.

Fuel cell technology for Hydrogen-electric technology.

Hydrogen electric powerplants are pivoting around fuel cell technology.

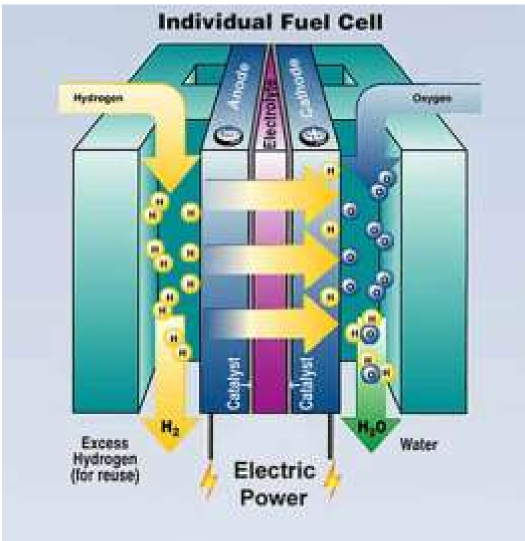


Figure 37. Working principle of a fuel cell (Fuel Cell Store).

Fuel cell thermal efficiency is continuously growing over the years, and it is expected to stabilize at around 60% by 2040.

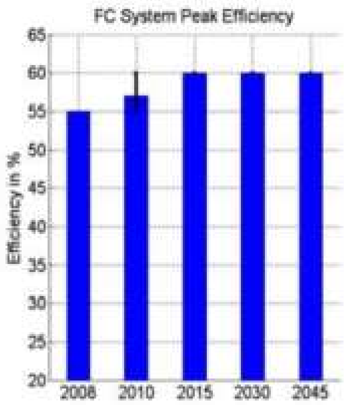


Figure 38. Fuel cell efficiency trend (Delorme et al., 2009).

Such value is higher than jet technological variants, however it is still lower than batteries for electric powerplants.

Technology-market interactions matrix

This step arises from the CFTP technique. The purpose is to consider some of the qualitative results of the previous steps of analysis and to translate them into a semi-quantitative evaluation.

Figure 39. Global aircraft fleet forecast by aircraft class (Cooper et al., 2019).

Figure 40. Short and medium-range flights cause two thirds of current aircraft emissions (FCH Europa, 2020).

Figure 39 and Figure 40 clearly show that in the future the most diffused aircraft classes will be narrowbody jets, followed from afar by widebody jets. Narrowbodies are also the most impacting aircraft category in terms of CO2 emissions.

Therefore, as suggested by Paap, the technology-market interaction analysis will focus on the highest-interest market segment: *Operators interested in short to medium-range flights and low payload capacity*.

Narrowbody jet airplanes, or their potential future substitutes, are developed for short to medium-range missions and limited payload capacity (approximately below 25 000 kg).

The selected market segment will be crossed with the most appropriate current product class according to the market development profile. The requirement is for powerplants fitted on aircrafts with 81 to 250 seats, capable of missions typically between 1 000 and 3 000 km range, and with low payload capacity. The product class covering such class on its own is *Turbofans*.

The technology market interaction matrix can be represented as follows.

Powerplant Performance Characteristic	Importance (technical)	Leverage (commercial)		Competitors					
				SAF Turbofan	Propfan	Hybrid - electric	Battery-Electric	Hydrogen Turbofan	Fuel-Cell electric
High thrust at low speed, at high airfield elevation, and at high outside temperature	4	1,1							
Capability to fly at high subsonic speed and high altitude	5	1							
Low weight and fuel consumption	5	1,5							
Small volume inside fuselage	3	1,2							
Low aerodynamic drag	4	1,1							
Low maintenance cost	4	1,4							
Low CO2 emissions	4	1,1							
Quick turnaround time	3	1,3							
High operational reliability rate	5	1,4							
TOTAL									

Table 9. Technology-market interactions matrix.

Powerplant performance characteristics are identified through literature research. In a real-life case, a team should be set up to discuss the selected characteristics, their importance from a technical point of view, their leverage from a commercial point of view (i.e., the degree of increased customer satisfaction on the improvements of a given characteristic), and the competing technologies.

The team should cover a 360-degree view in terms of skills and competences of participants. For example, it should include both technical experts, and representatives of airline operators.

A score ranging from 1 to 5 will be given to rate the importance level of each Powerplant Performance Characteristic. Leverage will be a multiplier ranging from 1 to 1.5.

In particular, some characteristic will be briefly explained more in detail.

High thrust at low speed, at high airfield elevation, and at high outside temperature.

Current turbofans suffer maximum thrust reduction as airfield elevation increases, due to lower air density. The same effect happens when outside air temperature increases, due to lower difference between the temperature of air crossing high-pressure turbine stages, and outside temperature.

So, a solution to mitigate such effect is to lower the maximum admitted payload of the aircraft, with operating and economic consequences.

Capability to fly at high subsonic speed and high altitude.

This is a must-have characteristic for the considered product class category, because at higher altitudes air is thinner, allowing for lower fuel consumption and higher ground speed.

Low weight and fuel consumption.

Powerplant overall weight is equally important. Every kilogram added to an aircraft requires more thrust to be generated to fly at the same conditions, and it increases drag; more thrust increases also fuel consumption, which requires more fuel to be stored inside the tanks, in a loop that heavily affects aircraft performance and operating costs.

About one third of the costs suffered by airlines is due to fuel.

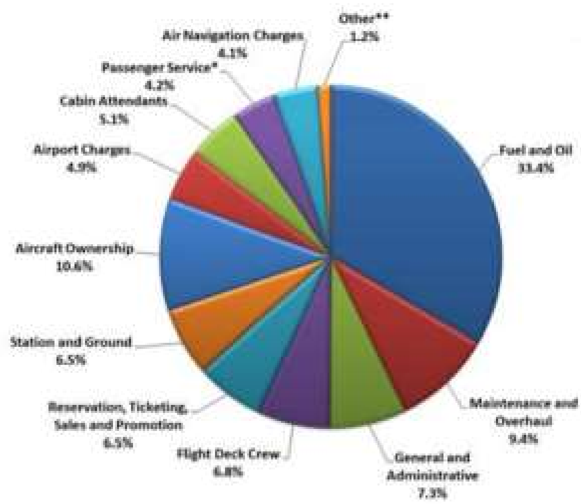


Figure 41. Airline cost structure (IATA, 2015).

Small volume inside fuselage.

Powerplant volume is less important than weight in terms of impact on performance. However, if inside the fuselage, it subtracts payload volume.

Low aerodynamic drag.

On the contrary, the higher the portion of the powerplant system outside the fuselage, the higher the aerodynamic drag it generates. So, the choice about the location of the powerplant or parts of it is a tradeoff between fuselage characteristics and aerodynamic characteristics.

Low maintenance cost.

About 10% of costs to operate an aircraft are related to maintenance, and in particular to power generation.

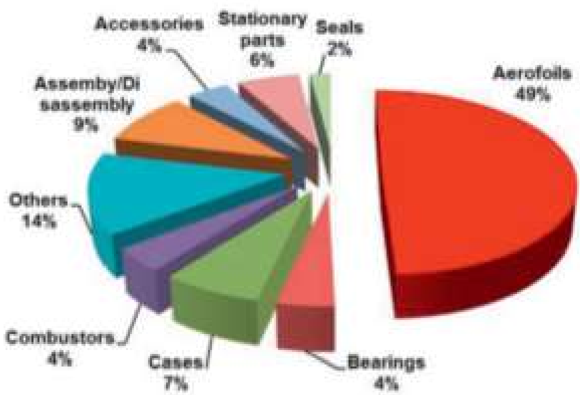


Figure 42. MRO Aircraft Engine Components Cost Breakdown (Morar et al., 2013).

High operational reliability rate.

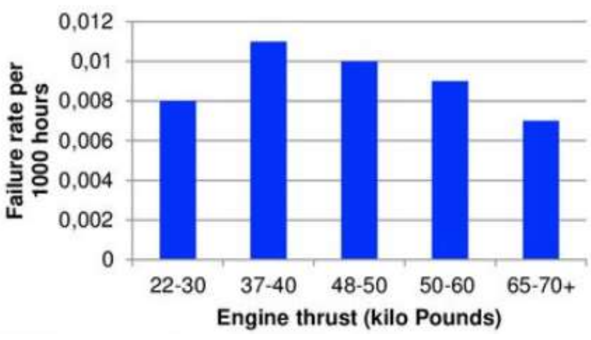


Figure 43. Probability of engine failure every 1 000 hours of operation (Petit, Ekstrand, 2018).

Current jet engines have an average reliability rate lower than 0,01 failures per 1 000 flight hours.

Competitor technologies need at least to match that value. Net of safety concerns, a powerplant failure event often results into an airport diversion, with its related costs such as passenger re-routing, airport fees, and crew replacement. Unscheduled maintenance and subsequent grounded aircraft also cause schedule disruptions or delays.

Technology impact matrix

Technologies that can affect performance characteristics are identified. Three main categories can be distinguished: Powerplant macro-components, Lifecycle, and Process Technologies.

The list of ingredient technologies is obtained by splitting the reference technology into the sub technologies characterizing it.

Process technologies primarily address airport infrastructures needed to provide ancillary services to aircrafts, and, specifically, to aircraft powerplants.

		Powerplant macro-components					Lifecycle			Process Technologies	
		Power generation	Drive chain and propulsion	Energy storage	Emissions reduction	Streamlined architecture	Powerplant production	Aircraft production	End of Life management	Refueling system	MRO facilities network
Competitor Profile Performance	SAF Turbofan										
	Propfan										
	Hybrid-electric										
	Battery Electric										
	Hydrogen Turbofan										
	Fuel-cell Electric										

Table 10. Technology impact matrix.

The same 1-to-5 rating scale already considered for the Technology-market Interaction Matrix is considered here to evaluate the level of maturity of each powerplant macro-component, each lifecycle-related technology, and each process technology applied to a competitor technology.

By intersecting the technology-market interaction matrix to the technology impact matrix, the comprehensive CFTP matrix can be completed, as in Table 11.

The highest among those three values corresponds to the most promising competitor technology according to the Semi-quantitative Analysis.

Powerplant Performance Characteristic	Importance (technical)	Leverage (commercial)	Powerplant macro-components					Lifecycle			Process Technologies		Competitors					
			Power generation	Drive chain and propulsion	Energy storage	Emissions reduction (during use phase)	Streamlined architecture	Powerplant production	Aircraft production	End of Life management	Refueling system	MRO facilities network	SAF Turbofan	Propfan	Hybrid - electric	Battery Electric	Hydrogen Turbofan	Fuel-Cell electric
High thrust at low speed, at high airfield elevation, and at high outside temperature	4	1,1	9	9	0	0	0	0	0	0	0	0	54	63	45	81	63	63
Capability to fly at high subsonic speed and high altitude	5	1	9	9	0	0	0	0	9	0	0	0	81	90	72	90	81	72
Low weight and fuel consumption	5	1,5	9	3	9	1	3	0	9	0	1	0	106	112	86	84	96	84
Small volume inside fuselage	3	1,2	3	9	9	0	9	0	9	0	0	0	117	135	81	78	102	84
Low aerodynamic drag	4	1,1	3	9	9	3	3	0	9	0	0	0	111	123	81	87	99	87
Low maintenance cost	4	1,4	9	3	3	3	9	3	3	0	3	9	138	150	99	105	114	102
Low CO2 emissions	4	1,1	9	3	1	9	1	3	3	9	1	1	129	133	95	124	124	111
Quick turnaround time	3	1,3	1	0	9	0	1	0	3	0	9	0	69	70	58	27	40	36
High operational reliability rate	5	1,4	9	3	1	1	9	3	3	0	1	9	118	130	85	91	98	86
TOTAL			**61**	**48**	**41**	**17**	**35**	**9**	**48**	**9**	**15**	**19**	**4783**	**5203**	**3645**	**3976**	**4231**	**3754**

Competitor Profile Performance		Power generation	Drive chain and propulsion	Energy storage	Emissions reduction (during use phase)	Streamlined architecture	Powerplant production	Aircraft production	End of Life management	Refueling system	MRO facilities network
	SAF Turbofan	3	3	3	4	3	3	3	3	3	3
	Propfan	3	4	3	4	4	3	3	3	3	3
	Hybrid-electric	3	2	2	2	1	3	3	2	3	2
	Battery Electric	5	4	1	5	1	2	1	1	1	1
	Hydrogen Turbofan	4	3	2	5	3	1	2	2	1	1
	Fuel-cell Electric	4	3	2	5	2	1	1	1	1	1

Table 11. CFTP matrix.

The intersecting cells are evaluated through a 1-3-9 scale, where 1 indicates a weak capability of the considered sub-technology to satisfy a given performance characteristic, 3 a moderate capability, and 9 a strong capability.

On the competitors' section, each cell is the sum of the products between the level of interaction of each technology and a performance characteristic, and the corresponding maturity level on the Competitor Profile Section.

So, the intersection between *Hybrid-Electric* and *High thrust at low speed, at high airfield elevation, and at high outside temperature* corresponds to the MS Excel *SUMPRODUCT* function between the values on the first row on the Technology impact matrix, and the values on the first row of the competitor profile section.

On the *TECHNOLOGY OVERALL EVALUATION* row, the *SUMPRODUCT* of the importance column, the leverage column, and the considered competitor's column is computed.

Results suggest that the most promising technologies are Propfans, followed by SAF Turbofans, and Hydrogen Turbofans.

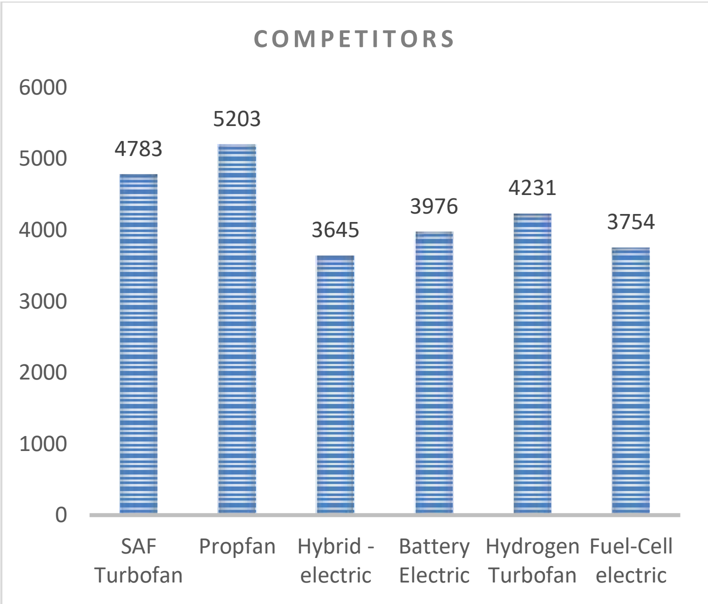


Figure 44. CFTP analysis results.

3.4 Quantitative analysis

Performance curves

A performance indicator needed to compare the considered technological variants is developed as follows.

Each parameter is weighted with respect to the less relevant one (weighting factor equal to 1).

Relevance is considered in terms of a purely technical perspective.

Four parameters are identified:

- Energy density expressed in Wh/kg, with a weighting factor of 4.
- Overall efficiency of power source and related drive chain, expressed by an adimensional value ranging between 0 and 1; its weighting factor is 2.
- Trust-specific CO2 emissions, expressed in g / (kN * s), with a weighting factor of 1.
- Cost of energy, expressed in $ / kWh, with a weighting factor of 3.

Results are obtained by processing values of the four parameters according to the following formula:

$$(\text{Energy density}^4 * \text{Overall efficiency}^2) / (\text{CO2 Emissions} * \text{Cost of Fuel}^3)$$

By collecting and processing such data as in *Appendix I* on current Turbofans and on the competing future technologies and their variants, the result up to 2022 is as follows:

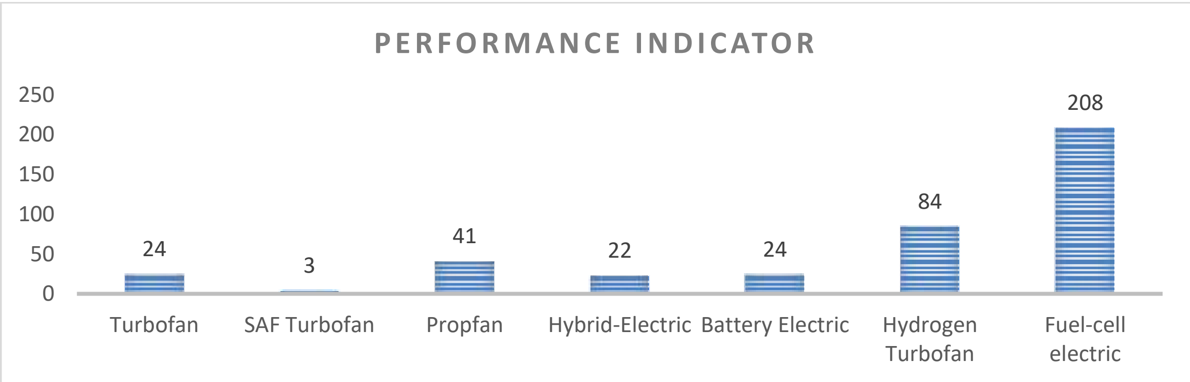


Figure 45. Performance indicator comparison with current data (*Appendix I*).

Performance values show remarkable degree of dispersion with respect to their average, 58.3, because they are not corrected by a damping factor.

Fuel cell-electric technology appears to be the most promising.

Plotting a performance curve over past years is not possible for competitor technologies, since in many cases there are not even prototypal powerplants fitted on aircrafts. Actually, there are only two propfans prototypal models performing bench tests.

Future performance curves can instead be plotted through the technological forecasting exponential growth model.

Since it is difficult to predict the growth factor *k* of each technology with good reliability, a sensitivity analysis is performed to assess the most promising technology by 2040.

Initially, the technologies are compared all with the same *k* value. In particular, the growth factor of Fuel cells k_f (the technology with the highest performance indicator value) is the same of the one of all the other competing technologies k_c.

Results are clearly in favor of the Fuel-cell technological variant.

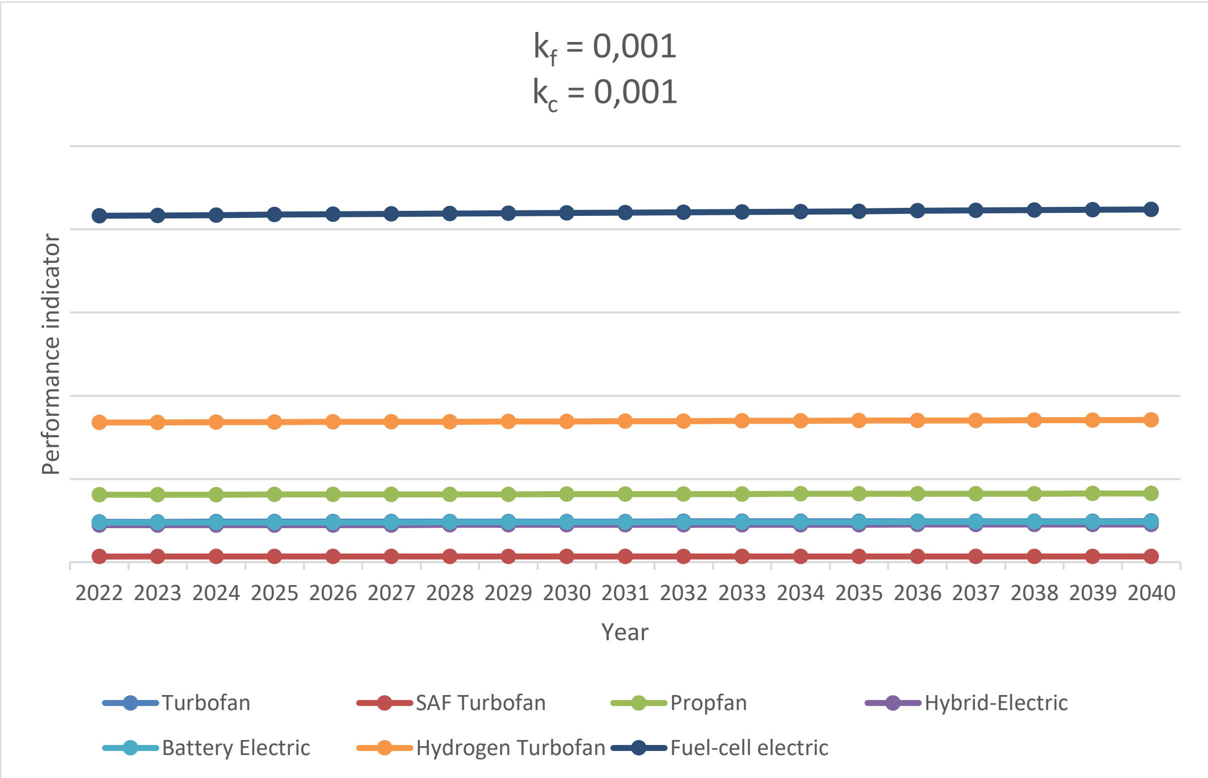


Figure 46. Forecasted performance curves with k_f = 0,001 and k_c = 0,001 (*Appendix II*).

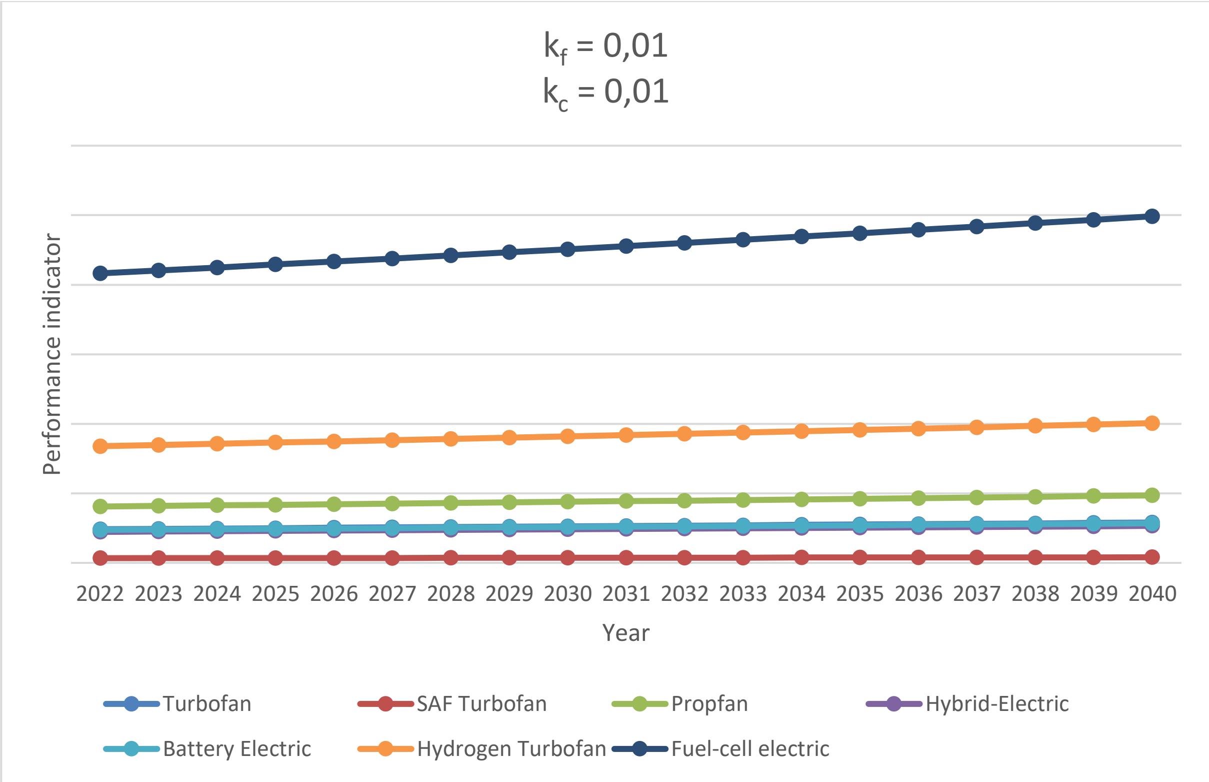


Figure 47. Forecasted performance curves with k_f = 0,01 and k_c = 0,01 (*Appendix III*).

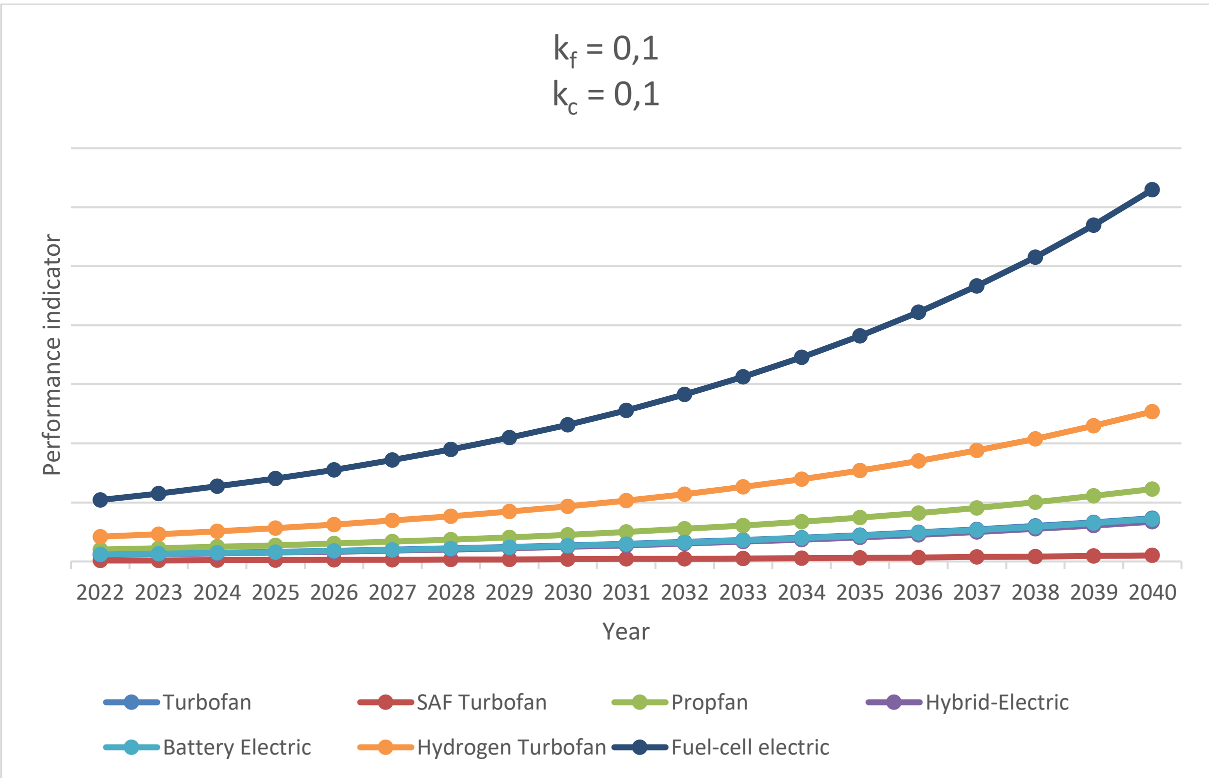


Figure 48. Forecasted performance curves with k_f = 0,1 and k_c = 0,1 (*Appendix IV*).

However, it is unlikely that every technological variant will have the same growth rate. Therefore, the growth rate of Fuel cell technology k_f is kept constantly lower that the one of all the other competing technologies k_c to evaluate any possible overtake in case of differential growth.

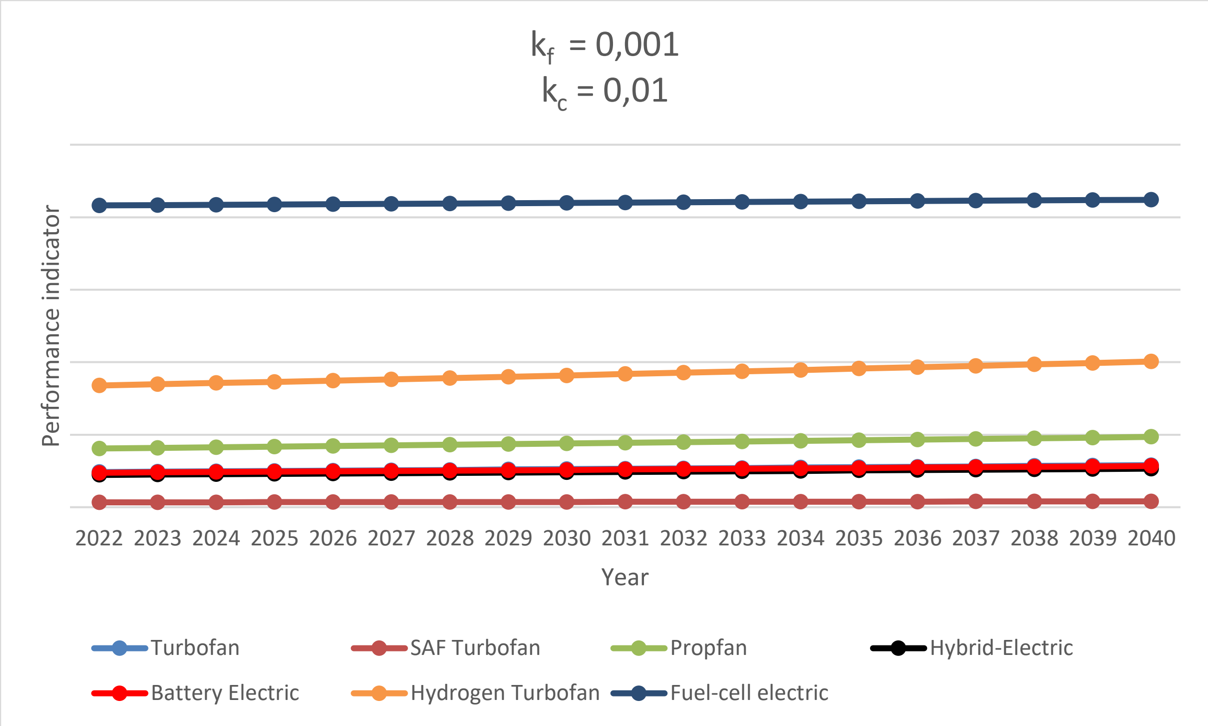


Figure 49. Forecasted performance curves with $k_f = 0{,}001$ and $k_c = 0{,}01$ (*Appendix V*).

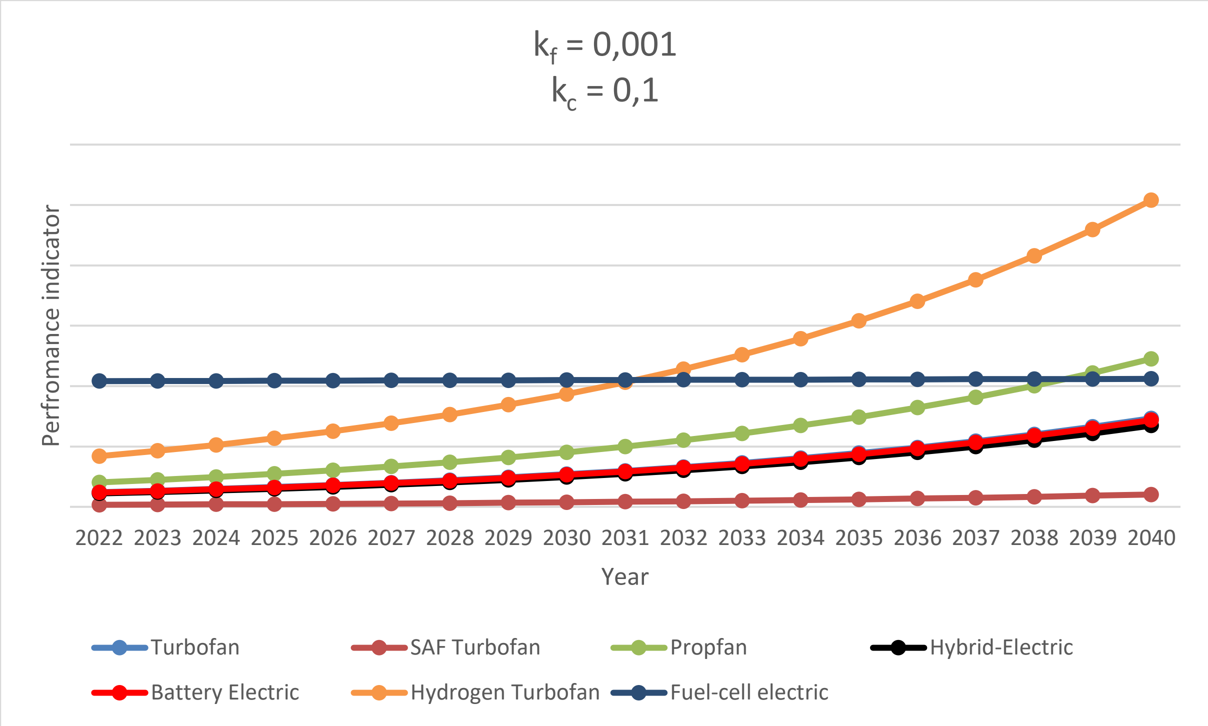


Figure 50. Forecasted performance curve with k_f = 0,001 and k_c = 0,1 (*Appendix VI*).

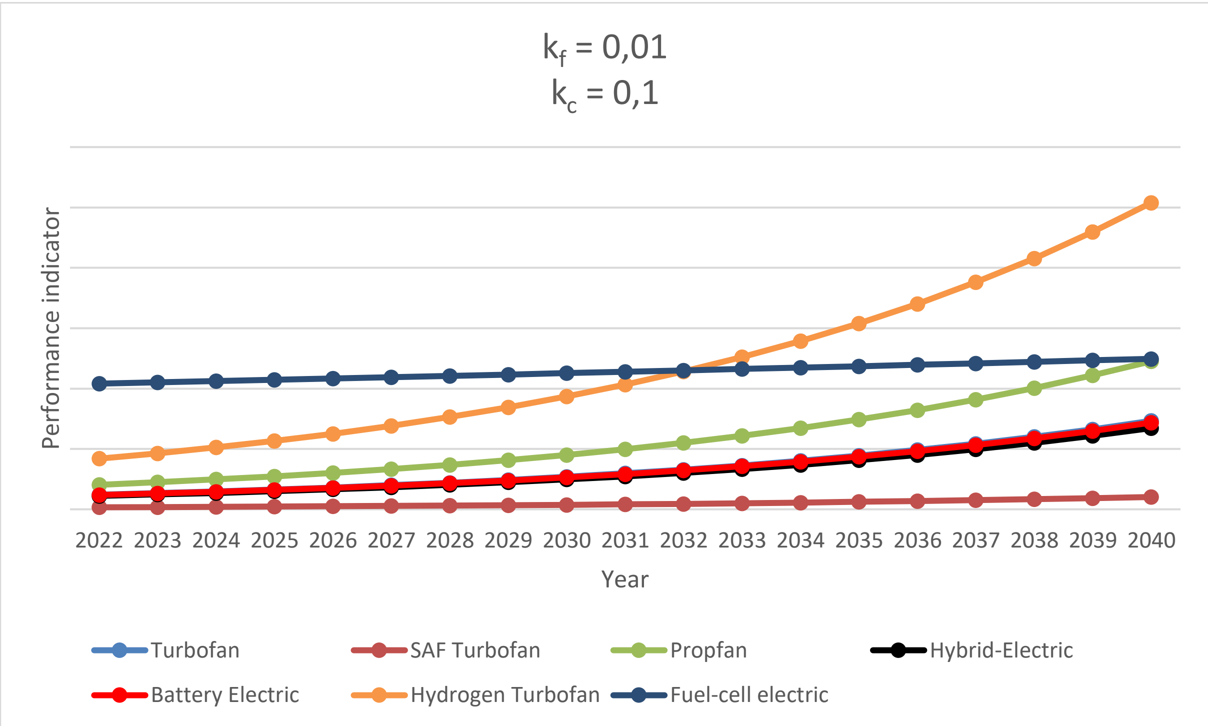


Figure 51. Forecasted performance curve with k_f = 0,01 and k_c = 0,1 (*Appendix VII*).

If k_f = 0,001 and k_c is at least two orders of magnitude higher, Hydrogen turbofan becomes the forecasted dominant technology.

If $k_f = 0{,}01$ and k_c is at least one order of magnitude higher, Hydrogen turbofan becomes again the forecasted dominant technology.

Rate of innovation curve

Turbofan technology is a mature technological variant, so, as expected, it has the lowest number of yearly new patents since 2000. Anyway, it shows a moderately increasing trend of new patents in the last decade.

Fuel-cell Electric, Battery Electric, and Hybrid-Electric score the highest numbers of new patents, indicating that the industry is focusing most of its effort on their development.

Full data set is available in *Appendix VIII*.

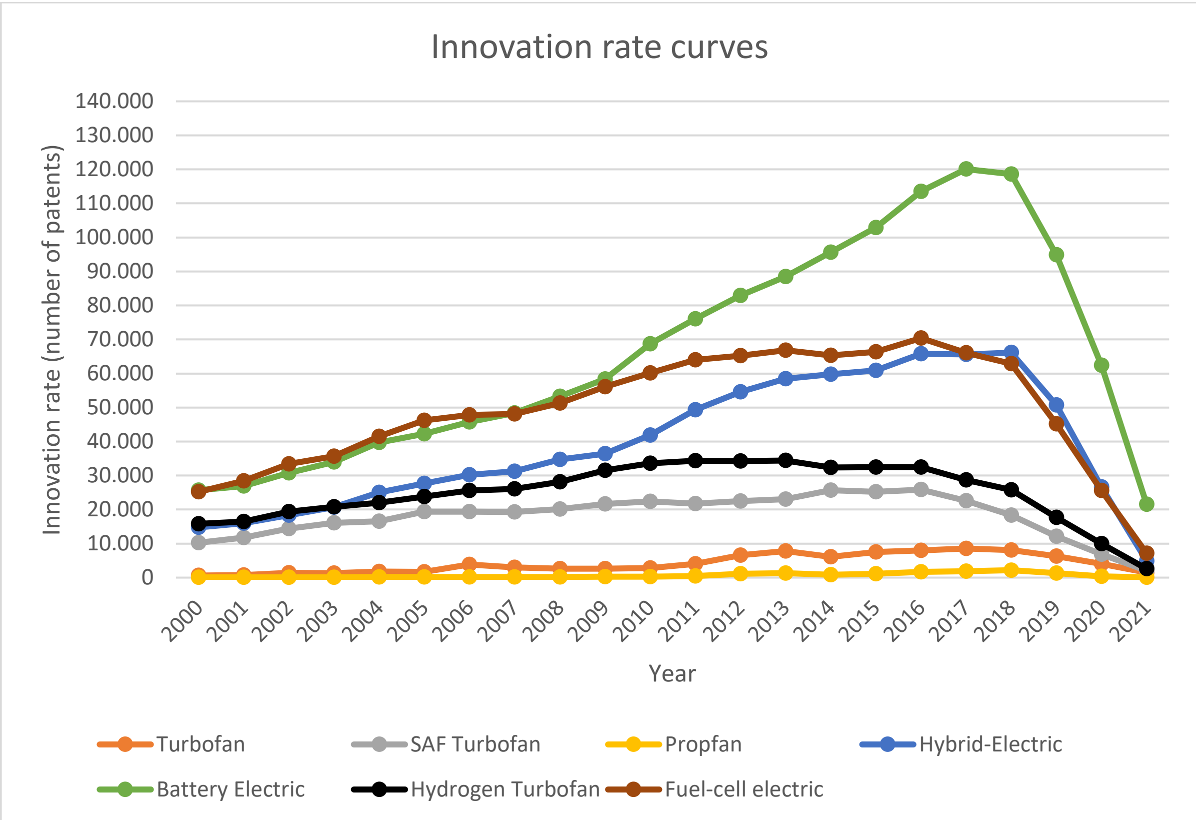


Figure 52. Rate of innovation curves since 2000 (*Appendix VIII*).

Figure 53. U.S. WTI futures price, constant dollars, 1983 - 2020 (World Oil, 2020).

Starting from 2019 new patents of every technological variant dropped. There can be many reasons for that, and a deep analysis of them lies outside the scope of the thesis. However, some hypothesis can be briefly described.

A possible explanation is the decrese of oil price between 2014 and 2016, which discouraged development of new engine technologies, because low oil price reduced the impact of fuel cost on airlines' balance sheet, and it allowed them to keep older aircrafts in their fleets. Then, Covid-19 fostered such trend, since it heavily affected aerospace industry and markets, as in Figure 54.

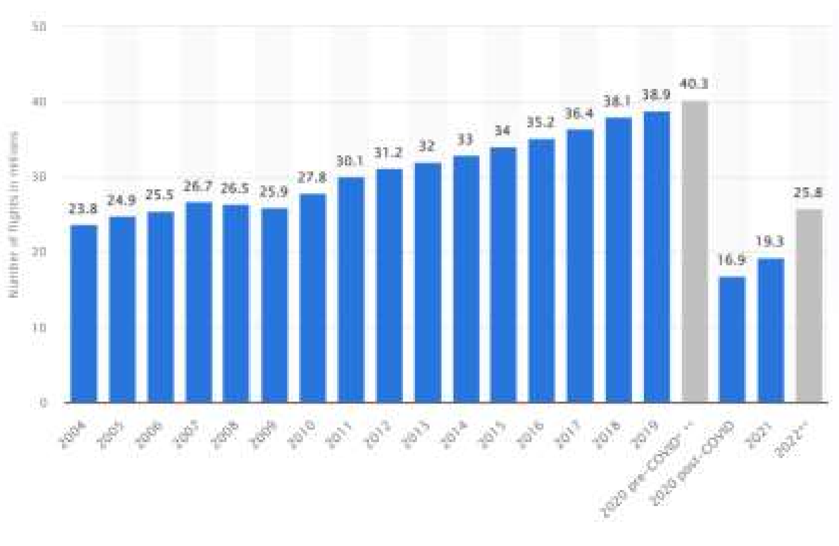


Figure 54. Number of flights performed by the global airline industry from 2004 to 2022 (Mazareanu, 2021).

3.5 Results refinement

Despite the lack of infrastructures and mature storage technology, Hydrogen technology, and in particular its Fuel cell variant, could represent the next dominant powerplant design by 2040.

Even in the case other technologies show growth rates at least one order of magnitude higher than the one of Fuel cells, the second most promising technology is again Hydrogen-based: Hydrogen-fueled turbofans.

A potential paradigm for the Fuel cell technological variant can be described as in Figure 55.

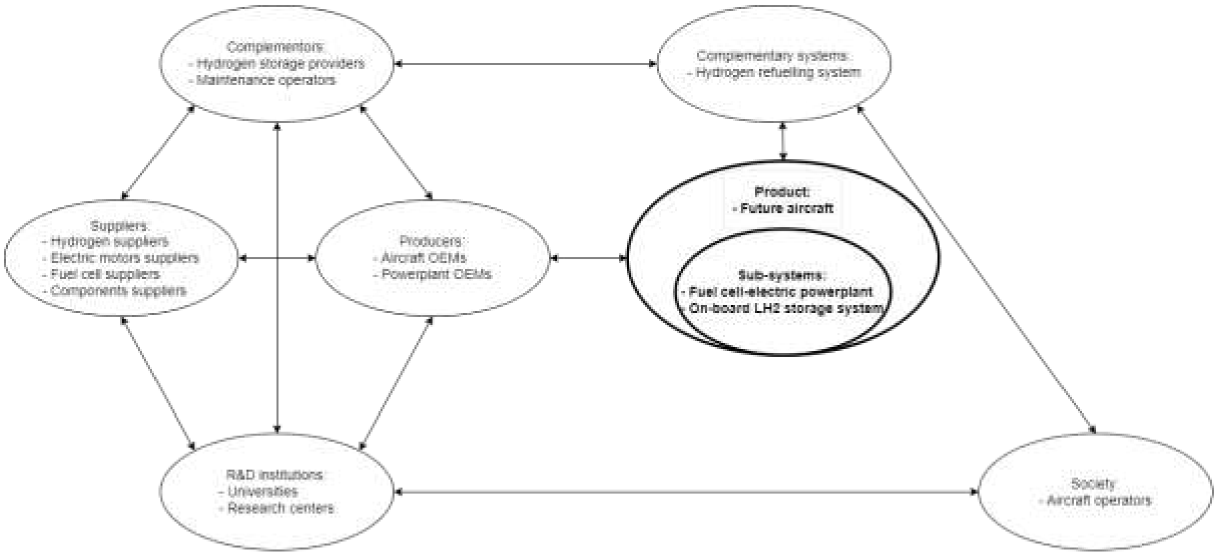


Figure 55. Potential technological paradigm for Fuel cell-electric aircraft powerplants.

Conclusions

By looking at the CFTP analysis results, future developments of the current reference technology, i.e., SAF Turbofans and Propfans variants, seem to be the most promising in terms of technical and commercial capabilities.

They are followed by Hydrogen turbofans, that keeps a similar architecture layout, but different core technology.

Battery-based technological variants (Hybrid-electric, and Battery electric) result to be less likely.

However, quantitative evaluations on technology development suggest that the market will shift to Hydrogen. The main strength is its high energy density, but energy storage capabilities are still low.

From a performance perspective, Fuel-cell electric powerplants could be the next dominant design, but they require a complete rethinking of the airframe on which they can be fitted. So, they will probably be the dominant design of new generations of aircrafts, such as the so-called blended wing body aircrafts.

For the short-term exploitation of a *Sailing ship effect* based on Turbofan capabilities could be predicted. Possible developments of Propfans and eventually Turbofans fueled by 100% Sustainable Aviation Fuel can be the solution.

Aknoledgment

I would like to thank Prof. Cantamessa for the assistance he offered me during the development of my thesis.

Thank you to my parents, for their endless support during all the past years since the beginning of my elementary school till now, through all the difficulties I encountered.

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In particular, thank you to Serena, Anna, and Riccardo, some of the few people I can really put my trust in.

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Appendixes

Appendix I. Performance indicator comparison with current data.

Technological variants	Energy density				
	Value (Wh/kg)	Parameter - Average	(Parameter - Average) / Standard deviation	Rescaled parameter	Weighted rescaled parameter
Turbofan	11900,00	-4530,86	-0,36	5,09	672,51
SAF Turbofan	11900,00	-4530,86	-0,36	5,09	672,51
Propfan	11900,00	-4530,86	-0,36	5,09	672,51
Hybrid-Electric	11900,00	-4530,86	-0,36	5,09	672,51
Battery Electric	216,00	-16214,86	-1,30	2,75	57,36
Hydrogen Turbofan	33600,00	17169,14	1,38	9,44	7938,41
Fuel-cell electric	33600,00	17169,14	1,38	9,44	7938,41
Average	16430,86				
Standard deviation	12480,62				
Weighting factor	4,00				

Overall efficiency				
Value	Parameter - Average	(Parameter - Average) / Standard deviation	Rescaled parameter	Weighted rescaled parameter
0,41	-0,09	-0,52	4,70	22,11
0,41	-0,09	-0,52	4,70	22,11
0,48	-0,02	-0,12	5,70	32,47
0,34	-0,16	-0,90	3,76	14,11
0,86	0,35	2,01	11,03	121,75
0,41	-0,09	-0,52	4,70	22,11
0,60	0,10	0,56	7,41	54,84
0,50				
0,18				
2,00				

CO2 emissions				
Value (g/kN/s)	Parameter - Average	(Parameter - Average) / Standard deviation	Rescaled parameter	Weighted rescaled parameter
6860,00	4410,00	1,55	9,87	9,87
1372,00	-1078,00	-0,38	5,06	5,06
5488,00	3038,00	1,07	8,66	8,66
3430,00	980,00	0,34	6,86	6,86
0,00	-2450,00	-0,86	3,85	3,85
0,00	-2450,00	-0,86	3,85	3,85
0,00	-2450,00	-0,86	3,85	3,85
2450,00				
2852,12				
1,00				

Cost of fuel					Performance indicator
Value ($/kWh)	Parameter - Average	(Parameter - Average) / Standard deviation	Rescaled parameter	Weighted rescaled parameter	
0,05	-0,15	-0,82	3,96	62,21	24
0,45	0,25	1,42	9,56	872,59	3
0,05	-0,15	-0,82	3,96	62,21	41
0,05	-0,15	-0,82	3,96	62,21	22
0,07	-0,13	-0,70	4,24	76,34	24
0,35	0,15	0,86	8,16	542,84	84
0,35	0,15	0,86	8,16	542,84	208
0,20					
0,18					
3,00					

Appendix II. Forecasted performance curves with $k_f = 0{,}001$ and $k_c = 0{,}001$.

	Year				
	2022	2023	2024	2025	2026
Turbofan	24,23	24,25	24,27	24,30	24,32
SAF Turbofan	3,37	3,37	3,38	3,38	3,38
Propfan	40,52	40,56	40,60	40,64	40,68
Hybrid-Electric	22,24	22,26	22,28	22,30	22,33
Battery Electric	23,75	23,77	23,79	23,82	23,84
Hydrogen Turbofan	83,92	84,01	84,09	84,17	84,26
Fuel-cell electric	208,18	208,39	208,60	208,81	209,02

Year						
2027	2028	2029	2030	2031	2032	2033
24,35	24,37	24,40	24,42	24,44	24,47	24,49
3,39	3,39	3,39	3,40	3,40	3,40	3,41
40,72	40,76	40,80	40,84	40,88	40,92	40,96
22,35	22,37	22,39	22,42	22,44	22,46	22,48
23,87	23,89	23,91	23,94	23,96	23,99	24,01
84,34	84,43	84,51	84,60	84,68	84,77	84,85
209,23	209,44	209,65	209,86	210,07	210,28	210,49

Year						
2034	2035	2036	2037	2038	2039	2040
24,52	24,54	24,57	24,59	24,62	24,64	24,67
3,41	3,41	3,42	3,42	3,43	3,43	3,43
41,00	41,05	41,09	41,13	41,17	41,21	41,25
22,51	22,53	22,55	22,57	22,60	22,62	22,64
24,03	24,06	24,08	24,11	24,13	24,15	24,18
84,94	85,02	85,11	85,19	85,28	85,36	85,45
210,70	210,91	211,12	211,33	211,54	211,75	211,97

Appendix III. Forecasted performance curves with $k_f = 0{,}01$ and $k_c = 0{,}01$.

	Year				
	2022	2023	2024	2025	2026
Turbofan	24,23	24,47	24,71	24,96	25,21
SAF Turbofan	3,37	3,40	3,44	3,47	3,51
Propfan	40,52	40,92	41,33	41,75	42,17
Hybrid-Electric	22,24	22,46	22,69	22,91	23,14
Battery Electric	23,75	23,99	24,23	24,47	24,72
Hydrogen Turbofan	83,92	84,77	85,62	86,48	87,35
Fuel-cell electric	208,18	210,28	212,39	214,52	216,68

Year						
2027	2028	2029	2030	2031	2032	2033
25,47	25,72	25,98	26,24	26,51	26,77	27,04
3,54	3,58	3,62	3,65	3,69	3,73	3,76
42,59	43,02	43,45	43,89	44,33	44,78	45,23
23,38	23,61	23,85	24,09	24,33	24,58	24,82
24,96	25,22	25,47	25,72	25,98	26,24	26,51
88,23	89,11	90,01	90,91	91,83	92,75	93,68
218,86	221,06	223,28	225,52	227,79	230,08	232,39

Year						
2034	2035	2036	2037	2038	2039	2040
27,31	27,59	27,87	28,15	28,43	28,71	29,00
3,80	3,84	3,88	3,92	3,96	4,00	4,04
45,68	46,14	46,60	47,07	47,55	48,02	48,51
25,07	25,32	25,58	25,84	26,10	26,36	26,62
26,77	27,04	27,32	27,59	27,87	28,15	28,43
94,62	95,57	96,53	97,50	98,48	99,47	100,47
234,73	237,09	239,47	241,88	244,31	246,76	249,24

Appendix IV. Forecasted performance curves with $k_f = 0,1$ and $k_c = 0,1$.

	Year				
	2022	2023	2024	2025	2026
Turbofan	24,23	26,77	29,59	32,70	36,14
SAF Turbofan	3,37	3,73	4,12	4,55	5,03
Propfan	40,52	44,78	49,49	54,69	60,44
Hybrid-Electric	22,24	24,58	27,16	30,02	33,17
Battery Electric	23,75	26,24	29,00	32,06	35,43
Hydrogen Turbofan	83,92	92,75	102,50	113,28	125,20
Fuel-cell electric	208,18	230,08	254,28	281,02	310,57

Year						
2027	2028	2029	2030	2031	2032	2033
39,94	44,14	48,78	53,91	59,58	65,85	72,78
5,56	6,14	6,79	7,50	8,29	9,16	10,13
66,80	73,82	81,59	90,17	99,65	110,13	121,71
36,66	40,52	44,78	49,49	54,69	60,45	66,80
39,15	43,27	47,82	52,85	58,41	64,55	71,34
138,37	152,92	169,00	186,77	206,42	228,13	252,12
343,24	379,34	419,23	463,32	512,05	565,90	625,42

Year						
2034	2035	2036	2037	2038	2039	2040
80,43	88,89	98,24	108,57	119,99	132,61	146,55
11,19	12,37	13,67	15,11	16,69	18,45	20,39
134,52	148,66	164,30	181,58	200,67	221,78	245,10
73,83	81,59	90,17	99,66	110,14	121,72	134,53
78,84	87,14	96,30	106,43	117,62	129,99	143,66
278,63	307,94	340,32	376,12	415,67	459,39	507,70
691,20	763,89	844,23	933,02	1.031,14	1.139,59	1.259,44

Appendix V. Forecasted performance curves with $k_f = 0{,}001$ and $k_c = 0{,}01$.

	Year				
	2022	2023	2024	2025	2026
Turbofan	24,23	24,47	24,71	24,96	25,21
SAF Turbofan	3,37	3,40	3,44	3,47	3,51
Propfan	40,52	40,92	41,33	41,75	42,17
Hybrid-Electric	22,24	22,46	22,69	22,91	23,14
Battery Electric	23,75	23,99	24,23	24,47	24,72
Hydrogen Turbofan	83,92	84,77	85,62	86,48	87,35
Fuel-cell electric	208,18	208,39	208,60	208,81	209,02

Year						
2027	2028	2029	2030	2031	2032	2033
25,47	25,72	25,98	26,24	26,51	26,77	27,04
3,54	3,58	3,62	3,65	3,69	3,73	3,76
42,59	43,02	43,45	43,89	44,33	44,78	45,23
23,38	23,61	23,85	24,09	24,33	24,58	24,82
24,96	25,22	25,47	25,72	25,98	26,24	26,51
88,23	89,11	90,01	90,91	91,83	92,75	93,68
209,23	209,44	209,65	209,86	210,07	210,28	210,49

Year						
2034	2035	2036	2037	2038	2039	2040
27,31	27,59	27,87	28,15	28,43	28,71	29,00
3,80	3,84	3,88	3,92	3,96	4,00	4,04
45,68	46,14	46,60	47,07	47,55	48,02	48,51
25,07	25,32	25,58	25,84	26,10	26,36	26,62
26,77	27,04	27,32	27,59	27,87	28,15	28,43
94,62	95,57	96,53	97,50	98,48	99,47	100,47
210,70	210,91	211,12	211,33	211,54	211,75	211,97

Appendix VI. Forecasted performance curves with $k_f = 0{,}001$ and $k_c = 0{,}1$.

	Year				
	2022	2023	2024	2025	2026
Turbofan	24,23	26,77	29,59	32,70	36,14
SAF Turbofan	3,37	3,73	4,12	4,55	5,03
Propfan	40,52	44,78	49,49	54,69	60,44
Hybrid-Electric	22,24	24,58	27,16	30,02	33,17
Battery Electric	23,75	26,24	29,00	32,06	35,43
Hydrogen Turbofan	83,92	92,75	102,50	113,28	125,20
Fuel-cell electric	208,18	208,39	208,60	208,81	209,02

Year						
2027	2028	2029	2030	2031	2032	2033
39,94	44,14	48,78	53,91	59,58	65,85	72,78
5,56	6,14	6,79	7,50	8,29	9,16	10,13
66,80	73,82	81,59	90,17	99,65	110,13	121,71
36,66	40,52	44,78	49,49	54,69	60,45	66,80
39,15	43,27	47,82	52,85	58,41	64,55	71,34
138,37	152,92	169,00	186,77	206,42	228,13	252,12
209,23	209,44	209,65	209,86	210,07	210,28	210,49

Year						
2034	2035	2036	2037	2038	2039	2040
80,43	88,89	98,24	108,57	119,99	132,61	146,55
11,19	12,37	13,67	15,11	16,69	18,45	20,39
134,52	148,66	164,30	181,58	200,67	221,78	245,10
73,83	81,59	90,17	99,66	110,14	121,72	134,53
78,84	87,14	96,30	106,43	117,62	129,99	143,66
278,63	307,94	340,32	376,12	415,67	459,39	507,70
210,70	210,91	211,12	211,33	211,54	211,75	211,97

Appendix VII. Forecasted performance curves with $k_f = 0{,}01$ and $k_c = 0{,}1$.

	Year				
	2022	2023	2024	2025	2026
Turbofan	24,23	26,77	29,59	32,70	36,14
SAF Turbofan	3,37	3,73	4,12	4,55	5,03
Propfan	40,52	44,78	49,49	54,69	60,44
Hybrid-Electric	22,24	24,58	27,16	30,02	33,17
Battery Electric	23,75	26,24	29,00	32,06	35,43
Hydrogen Turbofan	83,92	92,75	102,50	113,28	125,20
Fuel-cell electric	208,18	210,28	212,39	214,52	216,68

Year						
2027	2028	2029	2030	2031	2032	2033
39,94	44,14	48,78	53,91	59,58	65,85	72,78
5,56	6,14	6,79	7,50	8,29	9,16	10,13
66,80	73,82	81,59	90,17	99,65	110,13	121,71
36,66	40,52	44,78	49,49	54,69	60,45	66,80
39,15	43,27	47,82	52,85	58,41	64,55	71,34
138,37	152,92	169,00	186,77	206,42	228,13	252,12
218,86	221,06	223,28	225,52	227,79	230,08	232,39

Year						
2034	2035	2036	2037	2038	2039	2040
80,43	88,89	98,24	108,57	119,99	132,61	146,55
11,19	12,37	13,67	15,11	16,69	18,45	20,39
134,52	148,66	164,30	181,58	200,67	221,78	245,10
73,83	81,59	90,17	99,66	110,14	121,72	134,53
78,84	87,14	96,30	106,43	117,62	129,99	143,66
278,63	307,94	340,32	376,12	415,67	459,39	507,70
234,73	237,09	239,47	241,88	244,31	246,76	249,24

Appendix VIII. Rate of innovation curves since 2000.

	Year			
	2000	2001	2002	2003
Turbofan	615	740	1.368	1.356
SAF Turbofan	10.298	11.746	14.417	16.076
Propfan	81	121	96	115
Hybrid-Electric	14.803	15.969	18.384	20.734
Battery Electric	25.719	26.930	30.791	33.991
Hydrogen Turbofan	15.854	16.466	19.405	20.764
Fuel-cell electric	25.222	28.395	33.370	35.671

Year					
2004	2005	2006	2007	2008	2009
1.804	1.657	3.861	2.998	2.595,00	2.670,00
16.517	19.352	19.383	19.285,00	20.147,00	21.603,00
142	172	218	176,00	202,00	269,00
25.028	27.649	30.183	31.262,00	34.729,00	36.404,00
39.735	42.280	45.752	48.373,00	53.226,00	58.401,00
22.060	23.828,00	25.575	26.068,00	28.154,00	31.555,00
41.548	46.196	47.801	48.073,00	51.334,00	56.112,00

Year					
2010	2011	2012	2013	2014	2015
2.782,00	4.015,00	6.584,00	7.808,00	6.081,00	7.510,00
22.393,00	21.716,00	22.533,00	23.102,00	25.665,00	25.197,00
235,00	449,00	1.143,00	1.336,00	834,00	1.153,00
41.906,00	49.310,00	54.577,00	58.491,00	59.801,00	60.906,00
68.733,00	76.092,00	82.903,00	88.449,00	95.641,00	102.845,00
33.569,00	34.359,00	34.298,00	34.418,00	32.377,00	32.427,00
60.148,00	63.965,00	65.197,00	66.785,00	65.275,00	66.381,00

Year					
2016	2017	2018	2019	2020	2021
7.965,00	8.560,00	8.069	6.260	4.031	1.524
25.853,00	22.569,00	18.309	12.124	6.845	2.035
1.675,00	1.837	2.194,00	1.283	404	78
65.764,00	65.637,00	66.122	50.778	26.629	4.935
113.557,00	120.073,00	118.595	94.842	62.436	21.590
32.442,00	28.661,00	25.786	17.731	9.949	2.589
70.381,00	66.086,00	62.836	45.178	25.630	7.156