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Redefining Criticality in a Changing World

Combining Domestic and Global Perspectives on Enabling Technologies

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Abstract

In a dynamic geopolitical environment, policy makers need additional types of information when selecting technological domains for specific support. While all such selections eventually become political, they need to remain evidence-based to shield them against capture. This paper argues that the prevalent, nationally agnostic approaches to identifying critical technologies has become too unidimensional to sufficiently inform political decisions. Subsequently, it proposes a method to sufficiently acknowledge specific domains' domestic embedding and provides an overview of how its application to leading nations' patent data enables us to identify characteristic technological systems and specific decision-making challenges in Europe, the US and China.

1 Introduction

For decades, most political decisions on which technologies can be considered critical and hence worthy of specific attention have been negotiated by expert committees and panels (NNCTA 2023; Wagner et al. 2003), in part based on foresight and visioning (Keenan 2003). Overall, this reliance on aggregated but ultimately subjective expert assessments is not normatively problematic. In particular, towards the end of the process, political choices - or propositions - require the consideration of multiple perspectives that no simple 'model' can objectively integrate. In addition, they amount to a positioning that includes normative aspects and hence cannot be in a narrow sense 'evidence based'. Nonetheless, the danger of capture by sectoral politics of interest is real in all such processes (Edler et al. 2023), as is the risk that, unintentionally, myopic perspectives driven by technological optimism or fascination come to dominate. Even situation-related judgements based on sheer size, 'obvious impressions' or a perceived danger of external dependence can in these contexts never be fully ruled out. Against this background, it is essential that all such deliberations can start from a sound basis of evidence that provides relevant information in light of the challenges of the time.

Against this background, this paper will contribute to providing clearer and more differentiated baseline information to policy makers about to enter such processes of negotiation, while remaining conscious that the logic presented herein will be an additional, valuable basis for political deliberation, rather than its technocratic outcome.

In light of intensifying geopolitical competition and ensuing debates on technological sovereignty and strategic autonomy (Edler et al. 2020; Edler et al. 2023), the question of which technologies are to be considered *critical* enough to merit public support in and by specific countries has received renewed attention. In a swiftly changing and less reliable global environment, one of the key challenges in this regard has become how to better acknowledge technologies' *domestic* relevance.

When geopolitics were less of an issue, decisions on what merits support could and were largely taken based on technological grounds (Wagner et al. 2003). The most common approach at the time was to focus on technologies with general purpose characteristics that enable the development of novel solutions in multiple application domains ('key enabling technologies'; (Aschhoff et al. 2010; European Commission 2009). Sometimes, this perspective was combined with a view on dynamics, i.e. to what extent support only needed to add momentum in an already dynamic domain, or would have to help build foundations in a nascent one (Cozzens et al. 2010; Kroll et al. 2022). As long as a stable international division of labour could be taken for granted, in contrast, the integrity of the national technological system was not considered a fundamental criterion for public decision making.

As we grow more wary of the stability of an increasingly fragile geopolitical environment, however, political choices regarding the technologies that are to be supported can no longer follow a nationally agnostic logic. Unlike the past premise that different nations should form a global technological system with nexuses in different places, the question of how far certain integrative competences should be retained domestically and what specific technologies imply for the benefit of the respective nation is now receiving increased attention (Edler et al. 2023; March et al. 2023; NNCTA 2023).

As has been the case in emerging economies (Cho et al. 2011), and at times the United States (Wagner et al. 2003), policy makers in all leading economies will now have to consider more systematically and comprehensively how their support strategies fit with their domestic framework. While maintaining competitiveness and mastering digital and sustainability transitions remain the fundamental ambition of most nations' innovation policy (Haddad et al. 2023; Kanger et al. 2020;

March et al. 2023), policy choices can no longer primarily aim to optimise a country's contributions to a "global innovation system" (Binz et al. 2017).

As the global system becomes less reliable, more contested and more fragmented (Edler et al. 2023; Kroll 2024; Stiglitz et al. 2024), policy makers have to increasingly consider not only a technology’s generic transformative power, but also whether investments in that domain are likely to trigger broader effects locally as is or whether parallel efforts might be required to realise their full potential domestically.

In light of this, this paper suggests that technologies' integrating role in the domestic system shall become an essential additional aspect of political decision making, one that is already implicitly present in many recent reports (NNCTA 2023). If they provide strong interfaces with the respective nation's existing profile of technological strengths and thus 'hold the system together', this alone may now provide a rationale for supporting them, even if they fail to fulfil other, more traditional criteria for policy support. That said, the conclusion from current trends cannot be that the rationale of innovation policy must shift to a structurally defensive, nationalist rationale defying existing wisdom at the cost of autonomy (Edler et al. 2020; EPRS 2021; March et al. 2023).

Instead, they will have to follow a combination of different rationales, integrating established technological perspectives and that of national context in a combined approach in which inherent technological characteristics continue to stand at the centre.

Following this logic, this paper will begin by developing an extended conceptual notion of 'criticality'. It will outline that there are different 'groups' of critical technologies, associated with different political ambitions that they can help to achieve and/or with different generic approaches to support that are needed in order to become effective. Subsequently, it develops a methodology for the identification of these different groups that operationalises the above proposition.

To do so, we propose a patent-based methodology that classifies technologies along three main dimensions. First is a general purpose character. In line with earlier work on critical technologies (Kim et al. 2011; Kim 2017; Li et al. 2014), it considers its overall potential to enable solutions in other technological fields. Second is a networked positioning within the domestic knowledge pool. We ground our proposed classification on the "knowledge space methodology", which enables the analysis of the knowledge and technology structures in a given place and the way in which individual technologies refer to and integrate with them (Kogler et al. 2015; Kogler et al. 2017; Rigby 2015). Third is recent growth. In line with ideas put forward in earlier research (Daim et al. 2006; Kroll et al. 2022), it takes into account their current growth dynamic in order to separate static integrators from those with the potential to prompt structural change.

Applied to data from different national contexts, our analysis finds that the challenge for innovation policy will in some cases lie in choosing between strengthening different 'naturally emerging' domains that unite all three characteristics. In others, it may lie in the more challenging domain of deciding which of those enabling technologies that are not yet well integrated with the national technology system should be the focus of investment. At the same time, the methodology succeeds in delineating either group from those 'system integrators' which, for lack of dynamism, do not offer a future perspective and should hence at best be supported temporarily in transitory situations.

In passing, we develop a lucid illustration of how the European technology system integrates closely around a diverse set of technologies with and without general purpose character, whereas those of the US and China display a 'dual structure' that relies on a much smaller number of key drivers while most other technologies tend to be less locally embedded. While in the US and China many technologies are thus positioned as 'technologies with *potential* leverage', Europe features more technologies (and about as many patents) that combine all three aspects at the same time and may thus be worthy of support to reinforce strengths.

In the following section, we develop our conceptual framework which will lead to the definition of critical technologies. In Section 3, we explain the data and methodology used to identify critical technologies. Section 4 will show and describe the main results of our three case studies (Europe, United States and China). Section 5 will assess and discuss the findings and Section 6 will conclude.

2 Conceptual Framework

2.1 'Criticality': Central Differences in Notions between the Material and the Technological Domain

In recent years, the dynamic debate around technological sovereignty has reinvigorated an existing discussion around 'critical technologies' (Edler et al. 2023; EPRS 2021), which had lain idle after an initial peak during the early 2010s (Kim et al. 2011), at that time as a consequence of the key enabling technology debate.

Technological sovereignty can be understood as "the ability of a state or a federation of states to provide the technologies it deems critical for its welfare, competitiveness, and ability to act, and to be able to develop these or source them from other economic areas without one-sided structural dependency" (Edler et al. 2020). While it emphasises the inward-oriented target system of policy makers, it is thus primarily oriented towards capacities rather than dependencies or vulnerabilities (EPRS 2021).

Despite this early awareness that sovereignty should be considered through the lens of 'ability instead of autarky' (March and Schieferdecker, 2022), much of the debate around critical technologies became inspired by the parallel discussion around international material dependencies in 'critical raw materials' (Arjona et al. 2023; European Commission 2023; Ku et al. 2024; Tercero Espinoza 2023).

However, the criteria by which public interventions and public policies select and target certain technologies cannot be simply derived by borrowing the concept and methodology from the domain of 'critical raw materials' and translating it into the domain of technologies. In light of the conceptual notion of technological sovereignty put forward above, it requires a novel and fundamentally distinct heuristic approach.

As material goods, critical raw materials stand at the beginning of a production chain (Arjona et al. 2023; Ku et al. 2024). They are the direct or indirect material input for various resulting goods that cannot be produced without access to them and that may either be largely without technical substitute and/or very concentrated in their geographic availability (Arjona et al. 2023; Hofmann et al. 2018; Tercero Espinoza 2023). Conceptually, much of their 'criticality' derives from such factors relating to accessibility and substitutability (Tercero Espinoza 2023). Knowledge and technology, by contrast, do not unidirectionally stand 'at the outset' of anything. In circular and recursive processes of innovation, the lack of access to them will delay and obstruct, but hardly completely halt development processes. In addition, substitution by alternatives is much easier in the innovation domain than it can be in that of material production. Situations in which the use of one single technology for a specific purpose entirely without alternative are rare. Primarily, the limitation of access to knowledge will instead harm the evolution of future innovation processes, limit productive interactions and reduce diversity at interface, and hence serendipity and creativity.

Hence, our consideration of criticality in the technology domain requires a less unidirectional approach than is adequate for material goods. Its focus needs to be placed on technologies' multi-directional network centrality and bridging function within the constantly evolving technology space, as has, in principle, been earlier studies' assumption (Kim et al. 2011; Kim et al. 2012; Kim 2017; Kim et al. 2023; Li et al. 2014).

Secondly, technologies can have a transformative dimension by themselves, and their integration with the technology space is a bidirectional one. On the one hand, they have a status quo reference environment, much as 'critical raw materials' have a 'receiving' production system. On the other hand, their interaction with that environment is a bidirectional one with the potential to change and transform that environment in return (Kim 2017; Kroll et al. 2022). Accordingly, analysis of criticality in the technology domain must differentiate between a technology's current de facto embeddedness in the technological fabric of a specific economy and the fact that this results from the intrinsic, transformative potential that it could - theoretically - unfold in and for this environment, even if the respective links and reference structures are not yet present. In short, criticality assessments in the technology domain must therefore be developed with a focus on a dynamic, potential perspective, rather than with a focus on its current positioning in a given system alone.

A separate, yet related argument suggests that a dependency-based approach is also less pertinent than in the case of material goods. While material flows can be stopped, knowledge diffuses, even in the face of attempts to keep it secret. As history has shown, unintended leaks, active espionage and re-engineering can hardly be prevented. While knowledge flows can be restricted, e.g. through intellectual property titles, information cannot be completely withheld from third parties forever (Harhoff et al. 2003; Sorenson et al. 2006). Contrary to trade embargos that cause both immediate and lasting disruptions at the level of the flowing item, flows of technology can only be influenced indirectly if specific parties assume control of the development process by means of firm or intellectual property ownership. Even if such control enables some parties to exclude certain actors in innovation chains from specific aspects of knowledge on a temporary basis, this will not immediately halt existing processes of development. It will not disrupt a global innovation chain in the same way that a production chain can be disrupted.

In this paper, we therefore suggest that any method to identify critical technologies must start from the 'ability side' of things, i.e. a consideration of their inherent - and manifest - potential. 'Critical technologies' are those that are more central and enabling than others, both in general and for the national economy. Unlike raw materials, a technology does not in itself become critical because related competences are rare, held by unreliable partners or its development and/or production depends on resources that are scarce, or available from unreliable partners.

In the broader, overarching context of a changing, less reliable world order, the identification of critical technologies hence serves the purpose of identifying where a lack of technological sovereignty may pose, or potentially develop into, a *long-term issue* in terms of creating 'abilities'. It serves to identify breaking points in existing systems, the triggering of which may compromise their stability, and their ability to rebound (resilience). Whether external pressure already rests on these weak points is in a first step not essential for the identification of potential areas for support. As we will demonstrate, it may be added to the consideration in a second step - but primarily to inform the further selection between those technologies already identified as critical.

2.2 Leverage Points in the Technological Domain

For a long period of time, under the competitiveness paradigm, countries' performance in different technological domains was considered to be something that could be compared side by side as similar items. With the emergence of the notion of "key enabling technologies" during the late 2000s (Aschhoff et al. 2010; European Commission 2009), the subsequent all-pervasive digital revolution as well as new challenges in the domain of sustainability transitions, this understanding changed due to the acknowledgement that technologies - and even technological domains - are not equal, and hence not comparable on an equal footing (Kroll et al. 2022). Acknowledging this fact, and to better structure our thinking about criticality in the technological domain, this paper proposes three fundamental political rationales as to why some technologies could be considered more critical than others.

The primary aspect to consider is still their **inherent transformative potential**. Different technologies are to very different degrees relevant when it comes to mastering the key challenges that lie ahead of most developed societies today. While, from a competitiveness perspective, technologies used to be different means to the same end, the future development of societies and economies will depend on the question of whether they are fit for a specific purpose or not. Moreover, strengths in specific technologies are not only manifestations of ultimate capabilities but also the reflection of a capacity to transform the entire technological system - as one strand of technologies may be indispensable for advances in many others. Some technologies are enabling, even essential for other technological efforts, some less so. In the end, these differences and the differences in indirect impact potential that come with them may be even more relevant than the direct fit-for-purpose of a specific technology.

In addition, their **dynamics and presumed disruptive potential** are often discussed as a further criterion that justifies funding. The obvious problem with this is that it can hardly ever be known before the fact whether a technology may develop such a characteristic. Early signal scouting may help to guess which technologies will become disruptive in the future, but may be wrong and has been wrong, e.g. on nanotechnology and nuclear fusion. At the same time, it is very possible to assess the domains in which newly emerging technologies are likely to be more disruptive than elsewhere, since these domains are highly enabling themselves. In practice, this approach may help to identify the majority of future disruptive technologies. Furthermore, emerging dynamics can help to detect disruptive technologies at a rather early stage of the process of disruption before it is too late to react, as has been possible with regard to artificial intelligence.

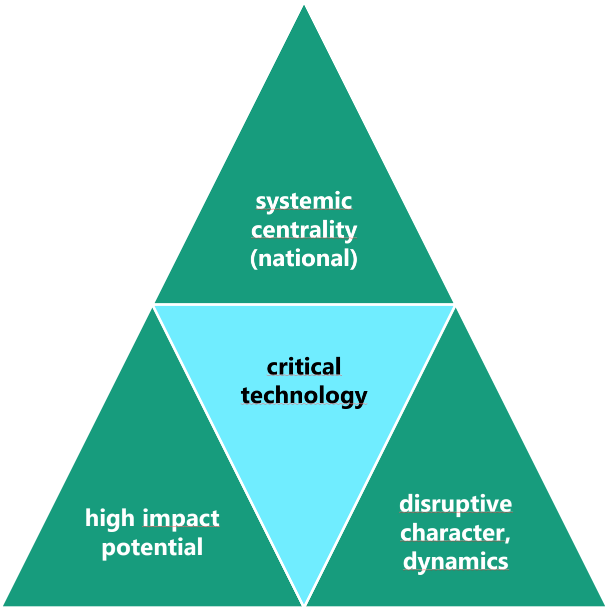
Finally, under the changing geopolitical framework conditions, technologies' (current) **systemic centrality for a specific national system** has become an additional, indispensable basis for decision making. More precisely, this refers to their structural role in providing bridges that 'hold the system together' by interfacing those technological domains in which the national system is specialised. While not identical, this fundamental consideration of 'anchor technologies' mirrors the way in which 'critical raw materials' are seen to matter for production systems. In a static world, this would be the primary criterion to identify critical technologies. In the absence of technological change, every country could give priority to those technologies that most help it to develop and maintain its comparative and competitive advantage. In reality, however, this may lead to misleading conclusions if the national technological system is outdated or losing dynamics. Nonetheless, all such systems have grown over time and follow path dependencies, and each of them must be transformed from its own, specific starting point. In cases where high-impact technologies have not yet moved into a system’s de facto centre, it will remain critical to master those that currently fulfil a central integrating function, i.e. to keep the system stable in the face of potential disruption while modernisation is gradually effected at and through the interfaces between existing and potential new anchor technologies.

In summary, critical technologies are primarily those that:

- have a high inherent impact potential,
- display dynamic growth, indicating that they may be or become disruptive,
- display a high level of current, systemic centrality in their national context.

While the concepts of centrality and embeddedness in the national systems have been widely used to define technologies and measure their relevance in the global or national innovation system, technology dynamics have rarely been brought into the discussion (Kim et al. 2012; Li et al. 2014). Including growth helps us make a step forward in the identification of critical technologies and develop a more comprehensive methodology that is able to capture the potential disruptive character of a technology.

Figure 1: Definition of a critical technology



Source: Own Concept

2.3 Analytical Propositions

On the basis of the more general considerations above, we propose that there should be three main groups of technologies that are critical in different ways and hence justify public support. Each one is based on a specific, distinctive rationale that may subsequently also motivate different types of interventions.

A first group is made up of technologies whose development fairly unambiguously deserves targeted political support:

- **self-emerging enablers**
  These technologies are highly enabling, central to the local system and grow dynamically. They deserve political attention if the intention is to reinforce strengths and add momentum to existing dynamics. Fostering their further growth may in practice not even require subsidies, as appropriate regulation to unfold their potential may suffice.
- **potential dynamic enablers**
  These technologies are highly enabling, dynamic as globally growing but they are not yet central to the local system. Their dynamic development might enable them to drive transformation, but they are not (yet) sufficiently embedded in the national system. Hence, support for them must be systemic, i.e. accompanied by broader investment that strengthens their relatedness to other activities.

A second group is made up of possible candidates for support where continued support could be required, although the actual necessity remains open at the current stage of development and hence requires further, more in-depth inquiry.

- **embedded enablers**
  These technologies are highly enabling, central to the local system but do not display strong growth dynamics. They could be nascent technologies that have *not yet* developed momentum but could do so as a result of policy interventions. However, they could also be old general-purpose technologies that have *started to lose relevance and will continue to lose* relevance to the national system.

- **catching up**
  These technologies are highly enabling but not central to the local system and not dynamic. Investments in some of these areas may be needed but will not be immediately effective in isolation, as generating momentum alone does not suffice. It will require substantive capacity building and a parallel structural development of the local system for them to become effective.
- **lasting interfaces**
  These technologies are central to the local system and sufficiently dynamic but less globally enabling. The observed dynamism can justify political support as such technologies often reflect application domains that will remain constant points of reference for enabling technologies. At the same time, support for them is, on its own, unlikely to provide much leverage to prompt development.

A third group is made up of technologies that may deserve transient support, the need for and relevance of which, however, can be clearly considered temporary based on their observable characteristics today:

- **transient bridges**
  These technologies are central to the local system but neither very dynamic nor globally enabling. In principle, they are therefore not predestined for political support and public investment, but they could be relevant to when it comes to stabilising the system during processes of transformation before they can be replaced. Their support should eventually be phased out if dynamism is unlikely to return.

In the following, the article’s empirical section will provide a reality check of the propositions outlined above, in light of what the literature tells us about the characteristics of the European, American and Chinese national technological and innovation systems (Chaminade et al. 2018; European Commission 2021b; Fagerberg et al. 2018a; Fagerberg et al. 2018b; Heimeriks et al. 2019; Lee et al. 2020).

It will do this first by developing and validating a robust operationalisation of the above notions that allows us to identify technology domains associated with the proposed conceptual categories in practice. Second, it will use this methodology to perform a comparative analysis of national contexts that introduces additional dimensions of analysis and demonstrates which sort of recommendations and policy insights can result from the approach proposed here - and which initial, tentative conclusions can be drawn based on it in view of nations' competitive positioning in the global economy.

3 Methodology and Data

As outlined above, our approach relies on a conceptual framework grounded in the technological domain. Hence, we chose to operationalise it in the technology space, i.e. based on patent data. The strengths and limitations of using patents for that purpose are known and shall, in this paper, not be repeated in detail. There could undoubtedly be some benefit in extending its empirical basis. However, our fundamental proposition that the domestic perspective matters – and our proposition for how it matters - can be demonstrated even within the limits of the pure technological space that patent data allow us to chart.

Methodologically, we follow earlier literature in reflecting a technology's global, enabling role through network-based approaches (Kim et al. 2012; Kim 2017; Li et al. 2014). In parallel, growth dynamics can be measured in a straightforward fashion. Finally, we leverage the relatedness density approach as developed in the recent geography of innovation literature (Balland et al. 2018; Boschma 2017) to capture a technology's domestic embeddedness and hence integrative power. In short, the above conceptual dimensions can thus be translated into measurable concepts as follows:

- role as enabler in the global technological system: centrality in the global network of patent co-classifications (details below),
- recent global growth dynamics: growth of patent applications in recent years, and
- role as integrator in a specific national innovation system: relatedness density, i.e. centrality with reference to the national technological portfolio.

As a first step, we collect patent data at country level from the EPO PATSTAT database for the years 2016-2018. The dataset contains patent applications data for 189 inventor countries and the technology classes used in each patent are classified using the International Patent Classification (IPC) at 4-digit level, for a total of 642 4-digit IPC technology classes.

The first dimension that we build allows us to assess the technologies' enabling character by determining their centrality in the global 'technological space' of IPC 4-digit classes, seeking to reflect the degree to which a certain technology is relevant to inventions in other areas or even serves as a broker between other fields. To do so, we first build a global technology space (Kogler et al. 2015) based on a network structure, where each node is represented by the IPC technology class (at 4-digit level), and each edge is represented by the number of patents on which both technologies (IPC 4-digit classes) occur in co-classification. We consider the network at a global level, accounting for all the countries in the database for the 2016-2018 period and all patent applications registered. To avoid counting the number of patents multiple times, patent counts are weighted proportionally by the number of IPC technology classes found on them. We build a non-directed and weighted network to capture the pattern of co-classifications at global level.

The indicator we build to measure the importance of a technology in the global technological system is based on two centrality indices: weighted degree centrality and the betweenness centrality. Weighted degree centrality is defined as the sum of weights assigned to the node's direct connections and represents the node strength. It captures the volume of the links between the nodes, which simple degree centrality measures (which only account for the number of direct links to the node) do not capture. It documents which IPC class is highly connected in the global technological system. Betweenness centrality captures the bridging power of a technology, denoting whether it lies in the shortest path within other technologies. Thus, high betweenness centrality implies high brokering power.

The final network index to reflect technologies' enabling character at a global level is calculated as the average value of the two measures, conveying a general message that will be the same for each technology class.

$$Global\ Network\ index_i = \frac{Node\ strength_i + Betweenness\ centrality_i}{2} \tag{1}$$

To reduce the skewedness of the data, we log-transform the global network index.

The second dimension is worldwide growth dynamics. As it is not possible to predict the future, the best possible alternative is to look at recent developments. To simplify matters, this first study looks at the relative growth rate for the last five years, correcting for outliers and statistical artefacts. For each IPC 4-digit class, we calculate the number of patents in all countries in 2015 and 2020 and calculate the logarithms of the relative growth of the number of patents in the last five years:

$$Relative\ growth_{it} = \frac{\log(patent_{it}) - \log(patent_{it-n})}{t-n} \tag{2}$$

The third dimension to define whether a technology is critical looks at the national technology system. Borrowing from the recent literature on regional diversification (Balland et al. 2018; Boschma 2017), we use the notion of relatedness density to establish whether a specific technology is not only enabling, but relevant to those technologies in which a specific country is specialised. This measure captures how well a technology is connected and integrated in the national system, being close to other technology classes and to those that are specialised in the country (Hidalgo et al. 2007). To measure it[1], we first build a national technology space based on an adjacency matrix of the co-occurrences between IPC 4-digit technology classes that belong to the country's patent portfolio. Based on this matrix, we calculate the relatedness, namely the proximity between technology i and technology j based on the number of co-occurrences, and adjust this number for the total number of co-occurrences of each of the objects of the matrix (van Eck et al. 2009). Following (van Eck et al. 2009), we choose association strength as a measure of proximity. This is most suitable as it provides a direct measure of proximity and, at the same time, corrects for size effects.

With the total number of co-occurrences of technology i defined as:

$$s_i = \sum_{j=1, j \neq i}^{n} c_{ij} \tag{3}$$

and the degree of relatedness calculated as:

$$S_{ij} = \frac{c_{ij}}{s_i s_j} \tag{4}$$

and the Revealed Comparative Advantage of each technology in the country, known as:

$$RTA_{ci} = \frac{patent_{ci} / \sum_i patent_{ci}}{\sum_c patent_{ci} / \sum_c \sum_i patent_{ci}} \tag{5}$$

assigned a $RTA_{ci} = 1$ when $RTA_{ci} > 1$,

the relatedness density for each technology i can be established by combining the degree of relatedness (4) of technology i in which the country c has the RTA (=1), divided by the sum of the relatedness of technology i to all the other technologies in country c:

$$Relatedness\ density_i = \frac{\sum_{j \neq i} S_{ij} RTA_{j1}}{\sum_{j \neq i} S_{ij}} \times 100 \tag{6}$$

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[1] To build the co-occurrence matrix and measure the relatedness density, we use the R package *EconGeo* (Balland, 2017).

The value of relatedness density lies between 0 and 100, the former meaning that there is no technology related to i in the country, the latter indicating that all technologies in the country portfolio are related to technology i. Therefore, this measure shows the extent to which a technology is integrated in the national technology space.

In line with the conceptual section's propositions, we can therefore identify three groups of technologies, list a selection of them and show their nationally specific distribution by plotting them in a 3-dimensional plane for different countries.

Group 1, safe candidates for support

- **self-emerging enablers**
  - positive values for all three dimensions
- **potential dynamic enablers**
  - positive values for the global network index and patent growth, but negative values for relatedness density

Group 2, possible candidates for support, requiring further inquiry

- **embedded enablers**
  - positive values for the global network index and the relatedness density, negative values for patent growth
- **catching up**
  - positive values only for the global network index, negative values for patent growth and relatedness density
- **lasting interfaces**
  - positive values for patent growth and relatedness density, negative values for the global network index

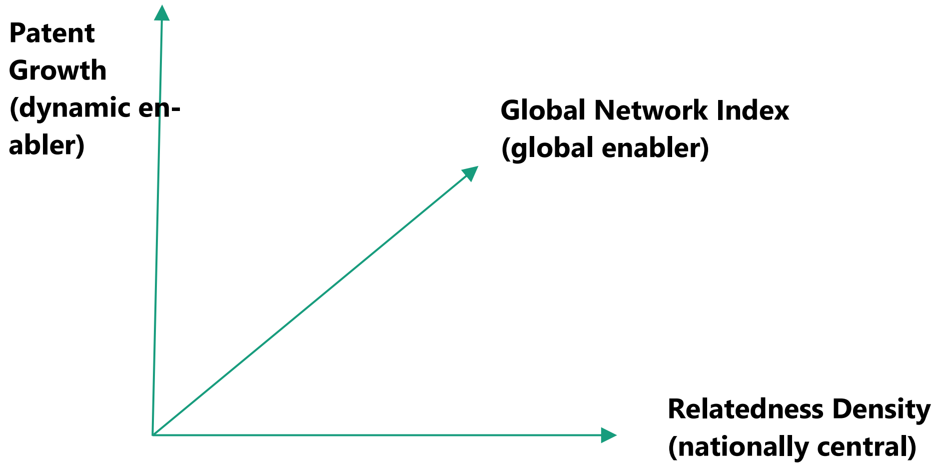
Group 3, candidates for temporary, transient support

- **transient bridges**
  - positive values for the relatedness density, negative values for the global network index and patent growth

All technological domains (4-digit IPC classes) that do not belong to any of the groups are dropped from the sample.

For illustrative purposes, we can plot the position of all technologies present in a country in a three-dimensional plane, illustrating their relative positions with respect to their level of national embeddedness, global centrality and growth dynamic (Figure 2). To ease comparability, we have fixed a range for all the axes within (-4,4) and corrected for outliers. Since our global measures of network and patent growth are calculated in logarithms, they follow a normal distribution, and they are quite comparable across the range since their mean is around 0 for both. Relatedness density, defined between 0 and 100, is rescaled directly to measures between (-4,4).

Figure 2: 3D plane with the three defined dimensions



Source: Own Concept

After all technologies have been assigned to the above groups, there will likely be too many remaining options in domains ‘worthy of support’ to enable straightforward decisions. Accordingly, we will demonstrate how additional information can be obtained for the 'initial selection' of technologies that can unambiguously be considered as critical.

In detail, we calculate:

- the percentage of patents for each technology class in Group 1 with respect to the total number of patents at a global level in that technology class;
- the share of international co-patenting activity, defined as the share of patents in each technology class on which inventors from different countries (for the co-cited technologies) are listed;
- and finally, we calculate the number of technology classes in Group 1 in which the country has an RTA above one (see equation 4).

4 Results

4.1 Critical technologies in major nations: Diverse options, distinct arrangements

In a first step, we apply our methodology to the European technology space as well as that of the United States and China. Table 1 shows aggregate technology fields (Schmoch 2008) in which IPC 4-digit classes are de facto found to be associated with the conceptual categories proposed above. The Top-5 listing is based on an index[2] of criticality based on summing up the standardised criticality values of three dimensions.

As self-emerging enablers, we identify classes from chemistry and special machines in Europe, pharmaceuticals and biotechnology in the US and such from computer technology and digital communication in China. With a view to the conceptual definition of the category, this is in line with expectations. As potential dynamic enablers, we identify other classes from the domain of computer technology, semiconductors, biology and audio-visual technologies, which, again, is in line with the conceptual definition of the category but, with a view to details, might already offer interesting differentiation, e.g. with regard to specific computer technologies.

As suggested, the second domain of fields that need further inquiry contain a mix of classes from modern fields alongside those from traditional, application-oriented sectors in a way that is also aligned with what is known about the specialisation profiles of the countries (Boschma et al. 2023; European Commission 2021a, 2021b, 2021c; Kroll et al. 2019). Alongside transport, communication and optical technologies, the area of 'footwear components' can be found here. This is possibly a reflection of a thriving trainer industry in the US, but still of a very different kind. As to be expected, the focus on traditional fields becomes even clearer in the third field, in which local embeddedness is the only rationale for potential support - as reflected in various established technologies from mechanical and electrical engineering, but also those for the making of "hats and head coverings".

Overall, the results can be considered as confirmatory based on what is known about the technological strengths, weaknesses and specialisations of the respective countries as well as the stage of development of their technological systems - as well as of our proposition that the heuristic approach proposed here provides comparatively direct indications for criticality in section 1, while this is less obvious in section 2 and 3, where further considerations would be needed.

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[2] Defined as the sum of the normalised scores (for the Global Network Index and patent growth) and the rescaled score (for Relatedness Density).

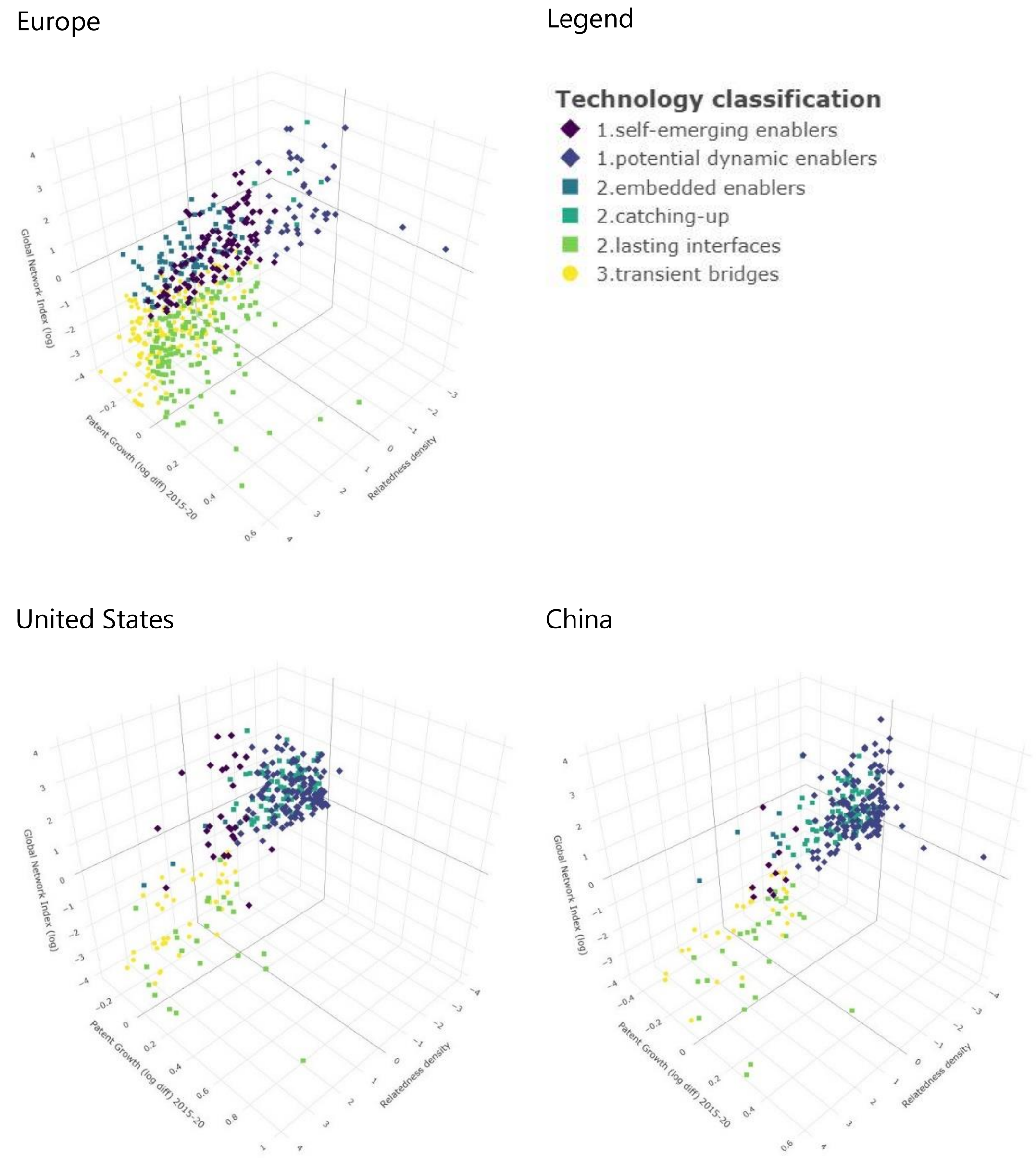
Table 1: Top 5 fields by country and technology group

Technology group	Europe	United States	China
1. self-emerging enablers (enabling, growing, integrating)	Agricultural biocides, repellants; Chemical separation processes; Surface technology, coating; 3D printing machines.	Pharma: compounds & preparations; Genetic engineering of microorganisms & enzymes; Medical technology.	Computer technology - memory devices; Telecom antennas, switches, relays, Wireless networks.
1. potential dynamic enablers (enabling, growing, NOT integrating)	Pharmaceuticals; Organic fine chemistry; Computer technology - image data reading; Semiconductors.	Analysis of biological materials; Navigational devices using radio waves; Optical elements; Semiconductors; Computer technology - image data reading.	Computer technology - image data reading; Telecommunications - transmission; Audio-visual technology.
2. embedded enablers (enabling, NOT growing, integrating)	Plastic reshaping machines; Transmission tools in vehicles; Handling - storage, packaging; Gearing, brakes, clutches.	Footwear components; Organic fine chemistry - methods and apparatus; Telecommunications - multiplex communication.	Basic materials chemistry - detergents; Lighting devices and systems; Telecommunications - telephones.
2. catching-up (enabling, NOT growing, NOT integrating)	Basic materials chemistry - lubricants and detergents; Digital information transmission; Telephonic communications.	Planes / helicopters; Organic chemical compounds; Materials for chemical applications; Optical devices for light control; Digital information transmission.	Vehicle brake control systems; Planes / helicopters; Optical devices and light control; Digital information transmission; Electrical machinery, - heating systems.
2. lasting interfaces (NOT enabling, growing, integrating)	Agricultural machines and devices; Railway vehicles; Chemical fertilisers; Textile and paper machines.	Machines to produce hats / head coverings; Basic chemistry - lubricants; Textile and paper machines; Computational chemistry; Bioinformatics.	Wood machines; Domestic refuse processing devices; Handguns; Image and video recognition; Cryptographic apparatus.
3. transient bridges (NOT enabling, NOT growing, integrating)	Cutting and multi-purpose machines; Vehicle parts and transmission elements; Engines, pumps & turbines.	Hats / Head coverings; Chemical libraries; Bullets and targets; Envir. technology - nuclear and X-ray; Engines, pumps & turbines.	Hats / Head coverings; Railway vehicles; Hydraulic engineering; Checking and registering devices.

Source: Own analysis based on EPO PATSTAT. Notes: Each field corresponds to one or more IPC4 classes. The abridged wording/labels used above are by the authors, based on WIPO - IPC class full names.

Subsequently, we analyse the overall distribution, patterns and mutual positioning of the proposed three groups of critical technologies in the technology space in Europe, the United States and China by plotting them in three-dimensional graphs (Figure 3) and by analysing the overall attribution of patents to them in Table 2.

Figure 3: Critical technologies as in Group 1, 2 and 3.



Source: Own calculation based on the developed definition and methodology.

When contrasting the technology spaces in Europe, the US and China, two rather different distribution patterns emerge. Europe's technology space appears well integrated, displaying a large and diverse group of self-emerging enablers as well as a large group of lasting local interfaces and transient bridges. It appears as a scattered cloud without a clearly defined centre. The United States and China, in contrast, have more unbalanced technology spaces, with higher concentrations of not yet fully integrated and potentially disruptive dynamic enablers (in dark blue and diamond-shaped).

With regard to the number of technology classes in each of the groups, we find that Europe displays a more balanced distribution across all three groups - and in absolute terms, the highest number of potentially critical technologies. In the United States and China, in contrast, the approach suggested here indicates a far smaller number of potential classes that can be considered critical. In Europe, a far higher number of technology classes are classified as "self-emerging enablers" (115) than in the United States (28) or China (10).

Table 2: Number of IPC-4 technology classes by group of technologies

N. of technologies in group	Europe	United States	China
self-emerging enablers	-115-	28	10
potential dynamic enablers	41	-128-	-145-
Group 1 Total	**156**	**156**	**155**
embedded enablers	-85-	4	7
catching-up	7	-88-	-85-
lasting interfaces	-151-	24	30
Group 2 Total	**243**	**116**	**122**
transient bridges	-153-	36	28
Total	**552**	**308**	**305**

Source: Own analysis

Table 3: Share of patents by group of technologies in the country

% patent by group and country	Europe	United States	China
1. self-emerging enablers	**38%**	**35%**	**11%**
1. potential dynamic enablers	20%	36%	60%
	58%	**71%**	**71%**
2. embedded enablers	**25%**	**1%**	**2%**
2. catching-up	4%	21%	20%
2. lasting interfaces	6%	0.5%	0.5%
	35%	**23%**	**23%**
3. transient bridges	5%	0.9%	0.6%

Source: Own analysis

Complementing this impression, Table 3 displays the share of patents attributable to the different categories proposed by this paper. Unlike Table 2, it documents that in China and the US, a larger share of patents falls into categories that can be considered critical in terms of offering potential (first group). This confirms common knowledge of those two economies' greater dynamism in key enabling technologies (European Commission 2021b; Kroll et al. 2022). At the same time, it contrasts in an interesting manner with the above finding that the share of technology classes under which this larger volume is subsumed is more limited than in Europe. This highlights that Europe faces an issue of greater diversity resulting - from a policy perspective - in a lesser obviousness of the technologies to be supported.

In addition, it highlights that while in Europe and the US at least half of all patents in dynamic areas with a strong enabling character occur in domains well integrated with the national technological system, that share is a mere 11% in China. In its still emerging economy, most critical activities occur in the area of "potential dynamic enablers", i.e. those not yet fully connected with the national industrial basis – which, in a similar way to the above findings on a more diverse and traditional European technology system, stands to reason based on what is known from the literature (Kroll et al. 2019). In a similar way, it outlines differences between a European system in which many patents in non-dynamic classes fall into the field of embedded enablers, i.e. well integrated fields, and a US/Chinese type of system in which patents in non-dynamic classes fall into the catching-up field, which, on top of a lack of dynamism, also lacks integration with the national technological system.

4.2 Which options to choose among the many: Critical technologies, competitiveness and cooperation

In a final step, we collect additional information on activities in the technology classes identified as self-emerging or potential dynamic enablers in different nations. Picking up on the challenge of great diversity in at least one of these two fields, it acknowledges that a classification based on technological characteristics cannot on its own suffice to inform policy decision making - arguably not even as an initial basis. While attributing technologies to groups must be the first step, further information is needed if the resulting core groups in part subsume more than 150 individual technology classes.

Accordingly, we identify relevant countries' share of world patent applications and the intensity of international co-patenting activity in the respective technology classes as well as the share of them in which the country displays specialisations. This analysis complements the above inward-looking, technology-trait and domestic embeddedness oriented with an outward-looking, national comparative perspective. The consideration of these three additional dimensions helps us to identify how each country performs in that group of technologies which the methodology proposed here identifies as most obviously critical. With regard to the implications for political choices in the face of more than a hundred potential options, it helps us to better gauge the practical economic leverage that certain, individual technologies may provide.

As Table 4 demonstrates, the findings for the different technologies subsumed under our proposed conceptual heading are quite diverse in all cases, in a way that even the general national framework only predefines to a very limited extent.

Europe, for example, is specialised in 77 out of 115 technology classes identified as self-emerging enablers. The individual technologies' share in global patent applications ranges between 8 and 62%, with fields like engines and machine tools reaching around 50% while Europe's contribution to the global total in others is far smaller. Similarly, the share of international co-patents ranges between 6 and 46%, with chemistry, biotechnology and materials reaching particularly high values. In contrast, Europe is specialised in only 8 out of 41 technologies classified into the group of potential dynamic enablers. Its share in global patent activities ranges between 3 and 36%, its share in international collaboration between 5 and 40%.

In the United States, almost all technologies classified as self-emerging enablers display an RTA above 1 (22 out of 28). Reflecting the size and development of the US economy, their share in global patent activity is never below 15% and at times reaches 50%. For the very same reasons, in contrast, international co-patenting activity is lower (4-30%). As in Europe, however, the US is specialised in only 30 out of 128 technology classes classified as potential dynamic enablers. Among these, the share in global patent activity ranges between 6 and 39%. The share of international co-patents among such US patents again ranges between 4 and 30%.

Finally, in China, only four of the ten technology classes classified as self-emerging enablers display an RTA greater than one. Their share in global patent applications ranges between 7 and 39%, with the highest percentages belonging to classes in the fields of digital communication, control, telecommunications and computer technology. The share of international co-patents in all activity is even lower than in the US with figures between 0 and 11% - with rare outliers (23%). Among China's potential dynamic enablers, 33 out of 145 classes display an RTA above 1. Their contribution to global patent applications varies between 2 and 60%, with a share of international co-patents between 0 and 37%. Compared to the US and Europe, China thus displays a lower tendency to collaborate internationally in patent applications, with very few, specific exceptions.

Table 4: Further info: global relevance, national importance and international embeddedness by group of technologies

% of technology in class	Europe	United States	China
Share with specialisation	**54%**	**33%**	**24%**
self-emerging enablers	67%	79%	40%
potential dynamic enablers	20%	23%	23%
Share in global applications	**28%**	**19%**	**14.5%**
self-emerging enablers	8-62%	15-50%	7-39%
potential dynamic enablers	3-36%	6-39%	2-60%
Share int. co-patents	**18%**	**13%**	**6%**
self-emerging enablers	6-46%	4-30%	0-23%
potential dynamic enablers	5-40%	4-30%	0-37%

Source: Own analysis

In summary, we find that our classification of technologies in specific classes is not indicative of their current, de facto role in the respective national system – which is good news with regard to using the latter as a secondary criterion in narrowing down options for political choices. Even if a technology must be considered unambiguously critical based on the logic suggested here, it can - at this point in time - be an absolute strength or a weakness, a specialisation or a side activity and - to a very different degree - the subject of international collaboration. This underlines that our methodology reveals facts that, if only obvious impressions were considered, might well have been overlooked. As Table 4 underlines, this holds true in general and independently for the world's three main economic powers.

5 Discussion

Picking up on earlier debates on how to select critical technologies (Daim et al. 2006; Kim et al. 2012; Kim 2017; Li et al. 2014), this paper proposes that potential areas for political support should, as a first step, be identified primarily with a view to their inherent technological characteristics rather than immediately with a view to a nation's specific positioning in an international context. It suggests that we should retain existing notions of key enabling technologies and transformation at the core of our thinking, rather than be tempted to borrow too readily from the parallel debate on raw materials.

In a first step of analysis, we confirm that our network-based approaches - developed in general analogy with earlier literature (Kim 2017; Li et al. 2014) - indeed yields plausible results for all major economic systems. At the same time, we demonstrate how adding a dynamic and, more importantly, an integration dimension helps to develop a clearer, less one-dimensional picture that is more useful for policy making.

In an international comparison, we find that Europe has a quite developed and diverse pool of critical technologies that rank high on all our criteria ("self-emerging enablers"), i.e. are well - integrated with the existing system and in individually specific ways. Despite their high number of patent applications in dynamic, enabling technologies, in contrast, the technology spaces in the US and China are characterised by a dual structure with a much more limited number of well-integrated key drivers (biotechnology, pharmaceuticals, digital communication, telecommunications), while the majority of dynamic key enabling technologies (computer technology, semiconductors, audio-visual technology, optics) does not display a high relatedness to the rest of the system. At least from a structural perspective, Europe may thus be less unfortunately positioned than public and scientific debates sometimes suggest. While this finding is indeed only logical considering Europe's greater number of specialisations, revealing this through the inclusion of domestic relatedness in our considerations and providing policy makers with an overview of its broader implications must appear necessary and important.

For example, the first impression that this leaves Europe with a greater number of potentially hard choices might be misleading. While Europe's industrial fabric may make more dynamic technologies self-emerging enablers, there is a consequence of this. If integrated well and without friction, they are unlikely to completely lose their dynamics, and policy support may in that sense not even be absolutely essential and/or require hard choices. And if a smaller number of technologies are in this favourable position in the US and China, this can have very practical implications for policy choices. While investments in the field of "potential dynamic enablers" may be potentially very transformative, they will require more substantial parallel efforts in related fields to become effective for the national system. As is, the inter-technology fabric that would transmit disruptions is not yet sufficiently developed. Hence, they may require expensive, parallel interventions into the development of the innovation system and, before that, hard choices in view of the limited resources. In that sense, the US and China may be confronted with a greater array of difficult options than Europe.

At the same time, our analysis reveals great complexity in the European technology space: While there are a large number of unambiguously critical technologies, more traditional and less dynamic fields ('lasting interfaces', 'transient bridges') also occupy a central position and subsume a higher share of patents than in China and the US. Likewise, a comparatively small share of patent applications in critical technologies is spread over many individual classes. Against this background, the seeming advantage of deep integration must also be seen critically - as the purported advantage of a greater number of leverage points may in practice be offset by the broader system's internal inertia - and the fact that the actual leverage brought to bear at these points remains too limited in many cases. This resonates with recent calls for a greater concentration of means to avoid diversity and complexity turning into fragmentation (Malanowski et al. 2021; Schubert et al. 2024; Weber et al. 2022). It also suggests that an additional focus on fields that have thus far been less embedded and have the potential to produce disruptive innovations ('potential dynamic enablers') remains important to trigger dynamic change.

Finally, we confirm that the resulting decision-making challenges may be assisted by drawing on additional information related to the international positioning of the country that does not empirically correlate with technologies' classification into the categories developed in this paper. Technologies in the same group can be absolute strengths or weaknesses, specialised or a side activity and to a very different degree the subject of international technological collaboration. While this lack of relation once more demonstrates how judgement based on pure size, 'obvious impressions' or external dependency can be misleading, it equally shows that they may add substantially as secondary criteria.

6 Conclusion

At a fundamental level, our analysis confirms that assumptions concerning criticality should not be made rashly based on technologically motivated visions, nor should it be derived defensively from a perceived threat of global dependency. Instead, both inherent characteristics of the technologies and the national technological system providing them with context can serve as the baseline for future decisions. That said, other factors - in part not covered here - will remain essential as secondary criteria.

As we have outlined, seeing technologies in the national technology space that embeds them is important to understanding their de facto transformative potential in a practical, rather than purely conceptual way. In addition, different national technology spaces result in different types of decision-making challenges. Depending on the fabric of the domestic technology space, it may be evident which technologies should be supported under a specific rationale in one country, while that very domain may present more options and require more careful deliberation in another.

In terms of limitations, this study operates in the patent space and is hence not able to consider aspects not reflected within that logic. The technometric method proposed here cannot account for external factors such as technologies' relevance for national security or sustainability transition. Likewise, it is outside the scope of our ambitions to identify black/white swan events like the emergence of large language models, which remain difficult to foresee even based on very recent dynamics.

Finally, our method classifies and identifies "technologies" on an IPC-based logic, which may not be sufficient to capture systemic interdependencies in all cases. As policy makers will often either be unable to focus interventions at that level of granularity or uninterested in doing so, the results of the proposed method should be considered as orientation rather than in a technocratic manner. From the granular picture of individual 'criticalities', systemic conclusions will need to be drawn.

If this context and the limitations are borne in mind, we believe that the method proposed here could serve as informative guidance to better structure our thinking about potential policy priorities in a way that is capacity- rather than vulnerability-oriented while also considering domestic context in the manner required today.

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