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Exploring the Geopolitical Limits of Responsible Innovation and Technology Assessment

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Abstract

The central argument of this paper is that the frameworks of responsible innovation (RI) and technology assessment (TA) are rooted in an antiquated political and geopolitical paradigm, thus necessitating a conceptual overhaul. This argument is supported by two primary reasons. First, RI and TA are not neutral towards technological innovation; instead, they inherently align with a specific political and geopolitical model: the liberal world order (LWO). This model currently faces significant challenges and crises, which I investigated through a literature review of RI and TA and a subsequent political and geopolitical analysis. Second, the very essence of our technologies has dramatically transformed over the past 20 years. We now live in a world dominated by intricate global engineering systems that are not only political but also geopolitical in nature. These transnational systems influence the decisions and interactions of nations. The current LWO framework struggles to effectively grasp and manage these influential global systems. In addition, this paper presents a reinterpreted version of Rodrik's trilemma. This reformulation was designed to consolidate and expand upon the insights already gained. It revisits the issues identified, emphasising the urgency of revamping both TA and RI, particularly in light of the unique challenges posed by the Anthropocene. As we embark on this reassessment, the invaluable insights from philosophical reflections should not be underestimated.

Keywords: Technology, Innovation. Democracy, Engineering Systems, Rodrik's Trilemma

Introduction

This paper delves into the political and geopolitical underpinnings of responsible innovation (RI), alternatively known as 'responsible research innovation' (RRI), and technology assessment (TA). The core argument is that these methodologies are anchored in a bygone political and geopolitical paradigm[1], the so-called liberal world order (LWO). The aim of this paper is not to underscore the significance of geopolitical influences on technological evolution, as this premise has already been established (Khan et al., 2022; Picado, 2022; Suchkov, 2022), but to illuminate the challenges posed by the decline of a specific geopolitical paradigm in the strategies for overseeing technological advancement.

The focus of this paper can thus be articulated as follows:

- What are the underlying political and geopolitical factors that influence the perception of innovation and its moral and social implications?

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- If these foundational beliefs are challenged or invalidated, what modifications should be made to our methodology?

To address these questions, this paper puts forward two hypotheses:

- Our current understanding of innovation and development, along with their associated responsibilities, is deeply embedded in a historical political and geopolitical framework that can be associated with the concept of LWO.
- The existing method of engaging with technological innovation becomes unsustainable over time, particularly as LWO undergoes a profound crisis and new frameworks emerge. This necessitates a re-evaluation and a novel approach to these issues.

RI and TA pre-suppose a specific political and geopolitical paradigm, the LWO, which has been established after the Second World War and is in deep crisis today. This claim is supported by a literature survey on RI and TA and a geopolitical and historical analysis. As I will demonstrate, the LWO has emerged as a political paradigm after the conclusion of the Second World War. It has weathered numerous challenges until the pivotal crisis in 2008, signalling its culmination and end. Thus, the LWO, predominantly shaped during the Cold War era, spanned roughly 60 years and has profoundly impacted the Western world. Over the past 15 years, we have observed the rise of a completely different geopolitical landscape. This new framework is marked by the decline of American supremacy, the ascent of illiberal powers, the surges of populism and technocracy, and the emergence of novel markets. What has been traditionally labelled as 'liberal-democratic solutions' now appears to fall short, as they no longer effectively address the challenges of our world and societies. Without a refreshed political and geopolitical understanding, the notion of 'responsible innovation' may become overly theoretical and lack practical impact. Embracing the concept of co-evolving technology and society, as proposed by Geels (2005), necessitates a thorough geopolitical re-examination of technology in a post-LWO era.

The second foundational argument revolves around the transformation of the essence of technology over the past two decades. In the current era, the world is governed by highly interconnected global engineering systems, also researched and discussed as socio-technical infrastructures in Science and Technology Studies (STS),[2] that hold significant political and geopolitical sway. These entities, operating on a transnational scale, play a pivotal role in shaping the decisions and dynamics between states. They manifest as expansive supply chains and communication networks such as the internet. The distinguishing feature of today's global engineering systems lies in their vast reach, ubiquity, and deep influence on political and social spheres.[3] Beyond their extensive influence, these modern technological networks also symbolise a shift marked by profound conceptual, historical, and philosophical alterations, encapsulated in the term *Anthropocene*. This paper posits that the LWO finds itself ill-equipped to comprehend and govern the intricate and expansive roles of global engineering systems, primarily because the existence of these systems undermines its foundational political principles. Consequently, the ongoing crisis within the LWO and the ascendancy of global engineering systems are intricately linked and mutually reinforcing phenomena.

Finally, I present the claim that these two aspects (i.e. the crisis of the LWO and the rise of global engineering systems) are connected and force the reformulation of Rodrik's (2011) trilemma, which concerns the very essence of contemporary capitalism. Rodrik's trilemma states that it is impossible to achieve all of the following goals at the same time: (1) deep economic globalisation with free circulation of capital, (2) national sovereignty, and (3) democratic politics. According to Rodrik (2011), any government must make a choice between two of these three elements. The crisis of the LWO and the growth of engineering systems have made it even more complex to arrive at a solution.

I must now clarify the nature of this research. First, in this paper, 'liberal world order' does

not mean that the 'liberal' thought has some moral or political superiority over other political predispositions. This paper does actually not intend to provide any moral or political appraisals. Second, in the following sections, I will use the terms *geopolitics* and *geopolitical*. These are quite controversial expressions for many reasons that I will not delve into here (see Kelly, 2006; Dodds et al., 2013). The epistemological status of the notion of 'geopolitics' itself is a much-debated topic for good reasons (see Flint 2021). As for this text, I limit myself to using the expressions 'geopolitics' and 'international affairs' almost synonymously. By employing both terms, I can cover a wider spectrum of discussion that includes both the strategic, geographical dimensions of state interactions (geopolitics) and the diverse aspects of state relations and diplomacy (international affairs). This approach ensures a comprehensive analysis that acknowledges both the physical constraints and the complex, multifaceted nature of global interactions.

Literature survey

The case of RI and TA

Over the past two decades, especially since the nanotechnology debate in the early 2000s, the expressions 'responsible innovation' and 'responsible research and innovation' have become commonplace in discourses and practices aimed at an inclusive, ethical, and transparent management of technological innovations. The discussion of ethics in science, technology, research, and innovation is not new, but the idea and practice of RI has been put forward only recently to incorporate democracy and responsibility into research and innovation policies (Stilgoe and Guston, 2017). According to Von Schomberg, RI is defined as "a transparent interactive process where societal actors and innovators become mutually responsible to each other, viewing the ethical acceptability, sustainability and societal desirability of the innovation process and its marketable products" (Von Schomberg, 2011: 9). The RI approach has been developed primarily in Europe through the efforts of the European Union, rendering it an essential element of its development and funding programs (e.g. Horizon Europe). Conceptually, this approach includes at least four dimensions: anticipation, reflexivity, inclusion, and responsiveness (Owen et al., 2021). Despite this, as Thapa et al. (2019) pointed out, the conceptualisation and operationalisation of RI remain ambiguous to some extent and at risk of being reduced to empty rhetoric. According to Van Lente et al. (2017: 3), RI is primarily an umbrella term "which connects different interests and viewpoints."

It is more complicated to provide a similar definition for TA, not only because TA has a much longer and more complex history (see Banta, 2009; Grunwald, 2019; Knezo, 2005; Sadowski, 2015; Van Eijndhoven, 1997), the roots of which go back to the 1970s (with the first Office of Technology Assessment being founded in 1974 by and for the US Congress), the 1980s (with many new institutions being initiated in Europe) and the 1990s (with EPTA, the European Parliamentary Technology Assessment, founded in 1990), but also because of the many forms of TA (e.g. participatory, health, hermeneutic, or constructive TA).

Generally, TA can be defined as a systematic and multi- / inter- / transdisciplinary process that evaluates the potential societal, economic, environmental, and ethical impacts of a technological innovation or advancement. According to Decker and Ladikas (2004: 14), TA is "a scientific interactive and communicative process which aims to contribute to the formation of public and political opinion on societal aspects of science and technology." In this definition, "particular emphasis is placed on unintended consequences—the non-obvious is to be made visible through interdisciplinary exchange, often involving stakeholders and those affected, and is thus made accessible for evaluation" (Hennen et al., 2023b: 2). TA involves the analysis of the development, implementation, and use of technology to provide informed insights and recommendations to policymakers, stakeholders, and the public. The primary goal of technology assessment is to inform decision-making, foster responsible innovation, and address the complex challenges and implications associated with the introduction and diffusion of new technologies (for an overview, refer to Grunwald, 2009; Vig and Paschen, 2000). In other words, the mission of TA

is "about reflection on technological progress, which should be used to enable a scientifically elaborated knowledge base for political decision-making, and social discourse on questions of shaping futures in an increasingly technology-dependent world" (Hennen et al., 2023b: 2). We can thus identify three dimensions of TA: a) the scientific, b) social, and c) policy dimensions. Connected to these three dimensions are three types of impact: a) raising knowledge, b) forming attitudes and opinions, and c) initiating actions (Hahn and Ladikas, 2019).

Methodology

What are the relationships between RI and TA? I assert that one can reasonably argue that RI is an outgrowth and advancement of TA because it incorporates tools originally developed within TA. On the other hand, Van Lente et al. (2017) proposed that RI serves as a critique of TA, involving a re-evaluation and modification of the objectives and methodologies of TA. This was not intended to question the origins of RI from TA but to provide a different interpretation. In particular, RI critiques TA in two key areas: the treatment of normative aspects and the consideration of stakeholders. According to Van Lente et al. (2017: 5), "[RI's] line of reasoning suggests that TA may overlook ethical complexities and underestimate the importance of guiding the direction of innovation."

The first objective of this research is to identify and analyse the basic political assumptions of these approaches, which I call, with a broader expression taken from Castoriadis (1974), their 'political imaginary'. To do so, I build on a literature survey regarding RI and TA. My literature sample includes 300 papers on RRI and 150 papers on TA that were published between 2017 and 2022. The articles were selected from the EBSCO and Google Scholar databases on the basis of the definitions and dimensions of RRI and TA. The objective of this survey was to conceptually investigate the connection between the two approaches and the so-called participatory democracy, liberal democracy, and public deliberation, as understood in the LWO architecture. NVivo software (2022 edition) was used in both cases for analysis.

I employed both quantitative and qualitative methods in my approach. Frequencies of occurrence of the following terms in the sample were measured: 'democracy', 'democratic', 'democratization', 'liberal', 'liberalism', 'EU (European Union)', and 'UN (United Nations)'. Frequency refers to the group of papers, not to individual papers; the same term can indeed appear several times in the same paper. Based on this methodological premises, I found that the terms 'democracy', 'democratic', and 'democratization' appeared 267, 255, and 245 times, respectively, in papers on RI, and 76, 69, and 85 times in papers on TA. The distributions of the terms 'liberal' and 'liberalism' differed, as they appeared 72 and 73 times, respectively, in papers on RI, and 45 and 38 times in papers on TA. It is also important to note the connection between the concept of democracy and major international institutions such as the EU and UN. References to the EU appeared in 254 papers on RRI and 103 papers on TA. On the other hand, references to the UN appeared 194 times in RI papers and 105 in TA papers.

Table 1 shows the term frequency percentages.[4] This gives us the average number of times each term appears per paper in each group, expressed as a percentage.

Table 1. Term frequencies in percentages.

Term	In RI papers (300)	In TA papers (150)	In the total number of papers (450)
Democracy	89%	50%	76%
Democratic	85%	46%	72%
Democratization	81%	56%	73%
Liberal	24%	30%	26%
Liberalism	24%	25%	24%
EU	84%	68%	79%
UN	64%	70%	66%

Qualitative analysis

As Owen and Pansera (2019: xii) pointed out, the political implications and/or foundations of RI have been little studied in the literature: "If RI aims for a different mode of science, innovation, and society, a different politics, what exactly is this mode, *what exactly is the political imaginary of RI?*" (emphasis added). This is why Owen and Pansera (2019) asserted the importance of a 'second-order reflection' about RI: "Without an understanding of how responsibility is framed, configured, and enacted, there is no 'responsible' in RI" (Owen and Pansera, 2019: 36). Indeed, as Owen and Pansera (2019: xiii) claimed, "RI's focus on science and technology has been at the expense of the very innovation systems within which science and technology development (and the institutions in which these are conducted) is increasingly located, increasingly implicated, increasingly complicit."

The simple analysis of occurrences and connections between terms could be misleading if it is not accompanied by the analysis of some representative texts that provide other useful elements for interpretation. As Yaghmaei and Van de Poel (2013) argued that 'responsible innovation' is not a clear-cut, clearly formulated principle or set of practices. Instead, it consists of a plurality of commitments, strategies, and interactions oriented towards the general objective of technological development aimed at socially desirable ends. The authors defined 'socially desirable' on the basis of UN or EU guidelines or norms. However, the UN and EU are products of the LWO, as they were conceived and designed on the basis of that geopolitical model; this is historical evidence (see, e.g., Acharya and Plesch, 2020; Kentikelenis and Voeten, 2021). Therefore, the crisis of the LWO carries the risk of emptying them of meaning.[5]

Rip (2018) thinks of RI as a model of social innovation that emerged in the late 1990s from the debate on nanotechnologies. Later, it became an umbrella term to indicate a series of approaches used mainly in the European policymakers' context: "RI implies changing roles for the various actors involved in science and technology development and their embedding in society. This is an important aspect of the social innovation of RI" (Rip, 2018: 126). According to Rip (2018: 126), dominant "is the utilitarian ethics perspective: maximise technology's positive contributions and minimise negative consequences. And a neoliberal version of it: it is enough if actors avoid causing harm." Rip (2018) also underlined the important role of the European Commission in developing this approach in research funding programmes. Moreover, Shelley-Egan et al. pointed out that 'responsible innovation' can "be considered to be ubiquitous within the EU's discourse around the governance of emerging technologies, cutting across, for example, subprogrammes within the European Commission's (EC) Horizon 2020 research funding programme" (Shelley-Egan et al., 2018: 1720).

Both the EU and the UN are institutional reactions shaped by the foundational values of the LWO. The purposes of these institutions are to propagate and modify the primary principles of the LWO for diverse global scenarios. Central to their mission is a core belief: the endurance and equilibrium of a specific societal structure hinge on striking the right balance between free markets, multilateralism, and democracy.

What is the relationship between TA and the political system in which TA operates? Hahn et al. (2023) described and highlighted the current and relevant developments of TA across 12 countries. The authors claimed that "the great heterogeneity of different country-specific settings in which TA takes place and is performed globally, cannot hide the fact that on a substantive and methodological level TA faces similar challenges" in all settings (Hahn et al., 2023: 25). On the other hand, "the question of the democratic quality of the political system and the rule of law seems to be a potentially useful predictor of the degree of TA institutionalisation, understood as the existence of fairly stable and formalised organisational structures and procedures within which TA is conducted" (Hahn et al., 2023: 26). Therefore, the authors applied the liberal democracy index of the V-Dem Institute to analyse the state of democracy in the countries under consideration. They concluded that "while any correlation between TA manifestations and scoring on the liberal democracy index should be treated with caution, we can observe that low scores on the index correlate with low

degrees of TA institutionalization, as is the case for India, China, and Russia" (Hahn et al., 2023: 28). In other words, where there is a stronger "liberal democracy, the TA is more institutionalized and stronger" (Hahn et al., 2023: 28). However, the authors also underlined that "the opposite relationship is not supported by our selected cases: a high rating on the liberal democracy index is not uniformly reflected by high degrees of TA institutionalization" (Hahn et al., 2023: 29).

The close tie between TA and liberal democracy is further underscored in recent discussions regarding the potential for a global TA. Hennen et al. (2023b) highlighted that the primary challenge for global TA is adapting the notion of TA as democratic policy guidance, rooted in Western traditions, to developing countries. These nations often differed significantly in cultural and political backgrounds, and typically lacked comparable economic capabilities (Hennen et al., 2023bThe resulting problems to be addressed, according to Hennen et al. (2023b), are numerous: How can we establish a sustainable global TA? What is the most practical and achievable approach to its development? How can TA tools gain traction in non-Western socio-economic and political environments? How can we ensure equitable collaboration among partners with economic disparities?

Let us delve deeper into this matter. Hahn and Ladikas (2019) clearly stated that the Enlightenment and 18th-century liberal traditions are foundational to the S&T policy in Europe. However, when conceptualising a global TA, there is a noticeable tension: the inclination to view TA as a universal method clashes with the necessity to pinpoint a specific environment where TA can operate and evolve. Crucially, TA is not merely a scientific pursuit; its objectives also encompass influencing viewpoints and guiding actions. Consequently, engagement with the social and political realms is indispensable. This means that the political system is essential to develop a good TA infrastructure; that is, TA is impossible in a dictatorship. Hahn and Ladikas (2019: 56) underscored the profound challenges that Eastern European countries confronted in attempting to establish and institutionalise TA after the momentous fall of the 'Iron Curtain'. Another significant remark is that the TA model, as cultivated in the Western world, "does not exist in the Chinese system" (Hahn and Ladikas, 2019: 126). While numerous public entities in China undertake activities reminiscent of TA, they lack the public and stakeholder engagement intrinsic to TA, specifically the component of public debate and deliberation. In China, activities akin to TA are encapsulated within an institutional framework primarily aimed at gauging economic growth, which is significantly different from Western political power structures. A similar argument can be made for Russia (Hahn and Ladikas, 2019: 190).

The problem of the relationship between TA and the political system has been addressed in many ways (Grunwald, 2019; Wong, 2016). Hahn and Ladikas (2019) explicitly asked, "Is TA possible in an illiberal system? Can we translate TA even in a non-democratic context? What are the normative bases of TA? Can non-Western ethical traditions be the foundation in S&T decisions?" These are crucial questions to understand whether a global TA is possible, that is, a TA that can transcend national borders and meet the challenges posed by globalisation. Undoubtedly, freedom of expression and the capacity for open discussion are pivotal to TA.

Furthermore, it is essential to integrate these elements within an economic paradigm that champions free markets and competition. The rationale behind this alignment is that technological innovation and progress, the primary concerns of TA, flourish most effectively in an environment characterized by these economic principles (further details on this relationship are explored later in this article). This consideration leads to a pertinent inquiry: Can TA be effectively implemented within an economic system that diverges from the principles of free market and competition?

Conceptual and operational references to the 'political imaginary' of RI and TA

On the basis of the previous analysis, I argue that there are two types of references to the 'political imaginary' of the liberal democracy model in the literature on RI and TA. The first reference is purely conceptual in nature. This is evident in Gianni's (2020) definition of responsibility as

the foundation of RI: "Being responsible means responding to the guaranteed freedoms as a recognised moral agent of a given society, having the aim of preserving such freedoms and at the same time implementing them through concrete institutional arrangements" (Gianni, 2020: 140). Moreover, the concept of responsible innovation presupposes the ideas of participation, engagement, and deliberation as means of solving collective issues. In this respect, RI and TA incorporate the deliberative democracy and communicative rationality model developed by Rawls (1971) and Habermas (1983) as the conditions of social engagement (Braun and Griessler, 2018; Reber, 2017; Scott, 2023; see also Van Est and Brom, 2012). Greater participation in public deliberation is explicitly demonstrated as the main way to steer social and technological innovation in TA (Hahn and Ladikas, 2019: 56). According to Hennen et al. (2023b), any public discussion weighing the advantages and disadvantages, potential outcomes, and ethical considerations of introducing and using technological advancements can be considered as an informal TA process (see also Rip et al., 1995). The centrality of public debate to liberal democracy was also underscored by Kelsen (2005; see also Tilly, 2007).

On the other hand, the second reference is more operational, as it describes how to translate concepts into norms and policies. This means that democratic deliberation is interpreted and realised in light of European and UN frameworks, and their values and goals (Cavas, 2015; Von Schomberg, 2013). In this respect, the process is reversed: the EU institutions have appropriated the weak conceptual architecture of RI by fully integrating it into their policy-making process (European Commission, 2013, 2014; 2019; European Council, 2009; Kop et al., 2023). Moreover, Hennen et al. (2023a: 234), when proposing models for a global TA, indicated that among the steps to be taken is the strengthening of the role of the UN in TA: "It is evident that the globalTA Network has a lot to gain by working with UNCTAD [the UN TA agency] while the opposite is also true." This means that RI and TA are not only theorisations of a political model but also ways of *doing politics* based on that model.

The main result of the previous quantitative and qualitative analysis is that RI and TA are not neutral approaches; rather, they are based on specific political assumptions about democracy and politics. This thesis intends to develop and improve the claims of Delvenne and Parotte (2018; see also Delvenne et al., 2011; Hennen, 1999), who argued that "TA communities should break with the myth of neutrality to render their political identity explicit and recognize that TA not only *has* politics, but also *is* political" (Delvenne and Parotte, 2018: 1). I claim that from a historical point of view, RI and TA are based on institutions that were born at the end of the Second World War, within a certain international political framework, the LWO. RI and TA can be considered an expression and extension of that political and geopolitical model. In the continuation of this paper, I argue that RI and TA must be updated or superseded, as the LWO model on which they are based is in crisis. In this respect, Lenoir's (2019) thesis that RI is an alternative to neoliberal governance confirms my claim. As we will see, neoliberal governance represents the crisis and end of the LWO.

Crisis of the LWO: A short narrative

TA and RI are generally framed as neutral analytical activities whose goal is to serve society and produce better technology, but this is just a myth. The purpose of TA and RI is to extend democracy and democratisation by implementing methods such as consensus, conferences, citizen summits, future panels, and scenario workshops. However, what is democracy from the perspectives of TA and RI? TA and RI imply a specific concept of democracy: liberal democracy, but what kind of liberal democracy? The one embodied by the LWO.

Over the past two decades, while various economic, political, and social crises have impacted the global arena, the deepest and most foundational has been the challenge to the LWO (Chadha, 2022; Duran, 2019; Lucarelli, 2022; Sinha, 2021; Snower, 2019). Rooted in Enlightenment values, the LWO began to crystallise in the immediate post-war years and solidified after the Second World War. Spearheaded by the United States and bolstered by the crucial involvement

of Western democracies, the LWO evolved and expanded from 1949 to 1989. This expansion manifested in a comprehensive web of international standards and institutions, the promotion of democratic governance within nations, the embrace of free trade, and the endorsement of multilateralism as the preferred mode of state-to-state collaboration and enduring cooperation. According to Gotz (2021), the traits of the LWO encompass the following: (i) a significant degree of security interdependence that promotes cooperation between states; (ii) a comprehensive framework of multilateral organisations that guide emerging powers towards alignment with the prevailing order; (iii) a global capitalist structure; and (iv) a widespread allure of liberal principles and administrative methods. All these traits are, to different extents, challenged by contemporary shifts in global politics. What are the causes of this crisis? What is the political logic behind the LWO?

As Parsi (2022) asserted, the LWO is a model of international relations architecture developed after the Second World War, arising from two distinct needs: the need to limit state sovereignty and therefore avoid new wars (indeed, to make peace economically utmost attractive) through the instrument of a free and internationally open market, and the need to regulate the free market, which, as was evident from the 1929 crisis, is incapable of self-regulation and can heavily undermine democracy (as was the case in the Weimar Republic and the rise of Nazism in Germany). Thus, the pivot of the liberal order was the alliance and balance between state sovereignty and the free market (Harvey, 2005; Ikenberry, 2020a; Reich, 2010). However, this balance is not just an end in itself. The balance between state sovereignty and the free circulation of goods and services, and between the needs of the democratic social order and those of economic competition had, in at least the theoretical intent of the LWO, to benefit, above all, a specific social subject: the middle class. A central aspect of the liberal project was the establishment of a strong middle class by improving the living conditions of a large portion of the working class. This also meant expanding rights, increasing social protection and political inclusion, and reducing economic inequalities.

This certainly does not mean that this system was just or perfect, or that it was 'heaven on earth'. The LWO tolerated or even favoured alliances with completely non-liberal political regimes, such as Franco's Spain, Salazar's Portugal, apartheid South Africa, and other dictatorships or religious fundamentalists around the world. Furthermore, the LWO was based on the US cultural, economic, defensive, and technological dominance, often to the detriment of the European partner. In other words, the balance between state sovereignty and the free market, which are "two powerful forces not necessarily inclined to natural harmony" (Parsi, 2022: 55), has always been fragile.

This international order began to unravel in the late 1960s and early 1970s. There were many causes, but I will limit myself to mentioning only four: the American defeat in the war in Vietnam, the oil shock of 1973, the end of the Bretton Woods agreements, and the implosion of the Soviet Union. According to Parsi (2022: 27), "it was here that the inversion from the original logic of the Liberal World Order also began in favor of the opposing one underpinning the Neoliberal Global Order: no more protecting domestic societies from the threats coming from the international environment, but rather shielding global markets—especially financial ones—from any interference coming from domestic societies." The reply to this change was formulated along three different but converging cultural–ideological lines: neoliberalism, neoconservativism, and ordo-liberalism (Parsi, 2022; Slobodian, 2018). The winning line was above all (but not only) a mixture of neoliberalism and neoconservatism supporting a market logic based on deregulation. This logic theoretically prescribed free competition but in fact protected the concentration of wealth and power. In this way, a transition from the freedom of the market to the 'dictatorship of the market' took place (Parsi, 2022: 66).

The 2008 economic crisis instigated a watershed, putting an end to the balance between sovereignty and the free market; it marked the beginning of the end for the LWO (Tooze, 2018). In chronological terms, the LWO peaked just after the Second World War and then

faced several crises (e.g. the oil crisis in 1973; see Schramm, 2023) until 2008, when its decline began. However, there are other interpretations as well. For Ikenberry (2020b: 133-134), the real end of the LWO was the COVID-19 pandemic: "The moment when the United States and its allies, facing the gravest public health threat and economic catastrophe of the post-war era, could not even agree on a simple communiqué of common cause. … The United States may no longer be the world's sole superpower, but its influence has never been premised on power alone" (see also Ikenberry, 2018, 2022).

The crisis of the LWO originated from the prevalence of the free market over state sovereignty, as demonstrated by the tendency towards deregulation of the financial system in Reagan's administration (Rasmus, 2020). It was accompanied by a profound crisis of democracy itself, with the emergence of what has been termed 'post-democracy' (Crouch, 2004): a system which, while remaining formally democratic, is characterised by estrangement of the masses from politics, the disappearance of the middle class, the emergence of increasingly cohesive oligarchies, and the progressive renunciation of the state to concretely intervene in the lives of citizens. These intertwined phenomena had several consequences such as the rise of power and influence of non-liberal nations like China; the redefinition of the US global strategy; the explosion of new protectionist and nationalistic tendencies; the crisis of international alliances and institutions like the NATO and UN; the growing financialization of the economy and state support for the banking system; the progressive decline in the quality of work with the spread of jobs characterised by insecurity, low wages, poor guarantees, and therefore a tendency towards greater debt; the growth of inequalities and the oligarchic transformation of the political system with a negative impact on the supply of public services (Piketty, 2013); the spread of populist, anti-establishment tendencies (on the nature of populism, see Urbinati, 2020); and the phenomenon of mass migration. Given all these fundamental shifts, "contemporary politics [has become] a game changer for TA institutions" (Delvenne and Parotte, 2018: 2) as well. Moreover, anti-establishment politics comes with serious epistemic effects, questioning the role of scientists and the scientific method, ideologizing debate, and creating conspiracy theories or false truths (Jasanoff and Simmet, 2017).

Now, I want to stress that the crisis of the LWO constituted a crisis of a global political strategy aimed at the harmonisation of two opposite logics. The crucial idea of the LWO, whether in its various liberal-American or European social-democratic versions, lies in finding and perpetuating an equilibrium between the market and democracy in the belief that the shortcomings of each system could be alleviated by the other. This meant finding a synthesis between two inverse logics.

The epoch of global engineering systems

In the past 40 years, owing mainly to the emergence and development of digital technologies, technological systems have become increasingly pervasive, complex, and powerful (see De Weck et al., 2011). Here is a more formal definition:

Engineering systems refer to complex, socio-technical systems that encompass the integration of technical and human components to achieve specific objectives. These systems are characterized by their focus on problem-solving within specific domains, such as transportation, healthcare, or energy. These systems typically require a multidisciplinary approach, bringing together expertise from different engineering disciplines and sometimes including non-engineering disciplines.

I propose to introduce a conceptual distinction between engineering systems and global engineering systems (GESs), composed of many interacting engineering systems. Engineering systems have always existed. However, today, these systems have reached a degree of complexity, ubiquity, and pervasiveness in human life that they have achieved a 'global' scope in both a quantitative (involving many different societies and nations) and qualitative sense (influencing and determining almost all major aspects of human life). They thus exert political power (Barry, 2001).

Therefore, GESs expand the concept of engineering systems to a worldwide scale, addressing global challenges and opportunities. These systems are not only interdisciplinary but also cross-cultural and international in scope. They involve collaboration across different cultures and nations, necessitating an understanding of diverse perspectives, regulations, and practices.

While engineering systems are primarily focused on solving complex problems within specific domains by integrating technical and human components, GESs extend this approach to tackle global challenges, requiring international cooperation, a focus on sustainability, and an understanding of global interdependencies. An example of GES is GPS, a satellite-based navigation system that provides location and time information globally, under any weather conditions, anywhere on or near the Earth where there is an unobstructed line of sight to four or more GPS satellites. It is a system of 24+ satellites in orbit, ground stations, and the devices that receive GPS signals. It involves several types of engineering systems: aerospace engineering, computer science, telecommunications, and more. Maintained by the United States government but accessible to anyone with a GPS receiver worldwide; its development and maintenance involve international agreements and cooperation. It is used across various sectors globally, including navigation for transportation, timing mechanisms in financial transactions, and disaster response coordination.

Owing to their power and complexity, GESs are not only political, but also highly geopolitical in the sense that they condition the decisions of national governments and the relationships between states. Another typical example of a GES is the internet, which began as a military application. Today, the internet is no longer simply an engineering system but something much more complex, involving many (maybe all) other socio-technical systems (energy, supply chain, business, etc.) and having social and political effects on a global, multi-sectoral and multi-dimensional scale.[6]

Another relevant example of GES is the International Space Station (ISS). The ISS is a model of international cooperation, a platform for the comprehensive study of the effects of long-term spaceflight on the human body, and a test bed for the technologies required for missions to the Moon, Mars, and beyond. It involves complex engineering and scientific collaboration among several space agencies, including NASA (United States), Roscosmos (Russia), JAXA (Japan), ESA (Europe), and CSA (Canada).

Five features of GESs are especially important here:

1. No one ever designs an entire GES. We only ever design a particular aspect of the system; designing consists of modifications or extensions to some existing element. Therefore, GESs are always a collective work; they are partially designed and evolved (De Weck et al., 2011: 31). Designing GESs "is essentially designing these specific interventions as levers that move the overall system into the direction we want it to go, which usually requires a model and understanding that spans several interventions and their interactions. Interventions can be seen as efforts or action(s) intended to secure a desired outcome or to change an outcome" (Maier et al., 2022: 9).
2. GESs have high internal complexity (i.e. these systems are composed of several elements, services, functions, and many intertwined hierarchical levels of organisation) and external interconnectedness. Furthermore, in these systems, different types of complexity are intertwined; therefore, new methodological approaches are needed to understand these new forms of complexity. We can distinguish at least three 'type sets' of complexity: technical, social, and human, and temporal complexity. I speak of 'type sets' because, for example, in technical complexity, we find many different types of complexity, including computational complexity, mathematical complexity, and complexity regarding design or material construction. The same thing can be said for social complexity, in which we find administrative and bureaucratic, ethical, political, social, psychological, genetic, and biological complexity, among others.

3. GESs have a global scope in the sense that they are not local; they go beyond a purely national logic limited to state boundaries. On the one hand, they are transnational, crossing national borders and involving different regions and states. On the other hand, they are often managed by private companies or by a cooperation between private companies and public authorities. Thus, GESs are not only the result of long chains of political and strategic decisions but also impose political choices and strategies over time that condition all players involved (states, individuals, organisations, and companies).
4. GESs are designed to last for several generations. Therefore, their design implies a vision of the future. However, future generations are not directly involved in the design process and cannot influence design decisions based on their, possibly own needs, values, and lifestyles.
5. In GESs, innovation cycles (including the conceptualisation, design, development, and marketing of new products and services) become shorter and shorter. This acceleration in innovation is driven by several key factors: 1) rapid advancements in technology, particularly in fields such as information technology, materials science, and automation, have drastically reduced the time required to prototype and produce new engineering solutions; 2) intense global competition motivates companies to stay ahead of the curve; 3) modern consumers have come to expect frequent updates and improvements in products and services, and this drives companies to release new iterations and versions of their offerings more frequently, responding to changing customer demands; 4) agile methodologies and iterative development processes have become prevalent in engineering and product development. The smartphone industry is a prime example of rapidly shortening innovation cycles.

However, it would be too simple to reduce GESs to this definition. In reality, GESs are also the expression of more than just an engineering super-system. They are the expression of a change of epoch and a deeper conceptual, epistemological, and ontological transformation, or what we call the 'Anthropocene'. From this point of view, I would say that the conceptual foundations of RI and TA would need to consider this philosophical transformation much more explicitly and thoroughly.

To defend this claim, I will first specify what I mean by Anthropocene. The general definition of this epoch is based on two basic assumptions: firstly, that "the Earth is now moving out of its current geological epoch, called the Holocene" and that "human activity is largely responsible for this exit from the Holocene, that is, *humankind has become a global geological force in its own right*" (Steffen et al., 2011: 843, emphasis by the author). This means that, secondly, "human activities have become so pervasive and profound that they rival the great forces of Nature and are *pushing the Earth into planetary terra incognita*. The Earth is rapidly moving into a less biologically diverse, less forested, much warmer, and probably wetter and stormier state" (Steffen et al., 2011: 614, emphasis by the author; see also Crutzen, 2002; Crutzen and Brauch, 2016; Crutzen and Stoermer, 2000).

Here, I consider Cera's (2023) thesis that the Anthropocene is a hyper-object characterised by epistemic and ontological instability.[7] The root of this instability lies in the fact that as such, the Anthropocene challenges the boundaries between natural and artificial, nature and culture, nature and society, and hard sciences and humanities, forcing a redefinition of these categories. This is "the definitive overcoming of the traditional clear distinction between nature (*physis, natura*) and culture (*techne, tecnica*), moving towards an osmosis/(con)fusion between the two", and this overcoming "should be considered as transcendental of the anthropogenic hypothesis: the Anthropocene's basic feature, a necessary premise for accessing it" (Cera, 2023: 19). As Australian cultural studies scholar Ben Dibley (2012: 140) claimed, "the Anthropocene is the crease of time." The advent of humans as geological agents "demands ways of thinking these temporalities [the deep time of geology and a rather shorter history of capital] together" (Dibley, 2012: 140; see also Cera, 2023; Chakrabarty, 2009, 2015, 2016, 2021).

These reflections are pertinent to the analysis of GESs. As I pointed out, GESs are also the expression of a new historical era, specifically the Anthropocene, and must be viewed through this lens to be fully understood.

The cage of Rodrik's trilemma

In this section, I offer a revised version of Rodrik's trilemma that serves both as a summary and an expansion of the earlier sections. I intentionally present this rephrased version in a simplified and formal way, akin to a logical theorem. This reformulated trilemma has a conceptual structure that compels us to acknowledge that the model of technology assessment put forth by RI and TA is not viable, drawing from the content discussed in the previous sections. The three logics of globalisation, state sovereignty, and democracy cannot exist together without at least one of them being compromised. Nevertheless, for a technological innovation and development model such as that suggested by RI and TA, we require the simultaneous presence of all three logics.

Even if we argue that globalisation has changed or is changing, the underlying paradox identified by Rodrik (2011) remains valid. The crisis of LWO demonstrates the fundamental rightness of the trilemma and proves that a balanced and responsible governance (i.e. based on the equilibrium of at least two of the elements of the trilemma) of technology is impossible. However, the emergence of GESs makes the development of a new geopolitically-oriented approach to technology and technological innovation urgent and critical.

Based on an analysis of the 1990 crisis in Argentina, Rodrik (2011: 42) reconstructed a fundamental tension between (hyper)globalization and democracy as "hyperglobalization does require shrinking domestic politics and insulating technocrats from the demands of popular groups." In other words, there was a clash between the international mobility of capital and companies (a basic feature of globalisation), and state sovereignty, which restricts politics to a geographically defined stable area. To justify this thesis, Rodrik pointed out different types of phenomena, such as outsourcing in the world of work; corporate tax competition (i.e. the competition between governments to attract companies and therefore the progressive shifting of the burden of taxes from capital to labour); differences between health and safety standards; and restrictions on industrial policies for the poorest countries (a fact that emerged above all in patent and copyright regulation; Rodrik, 2011: 189–199 for all these aspects).

On the basis of these remarks, Rodrik developed his trilemma. The three actors in the trilemma respond to different, and partly incompatible logics. Foremost, the logic of globalisation is incompatible with both state sovereignty and democracy. Overall, we are left with three options: "If we want hyperglobalization and democracy, we need to give up on the nation state. If we must keep the nation state and want hyperglobalization too, then we must forget about democracy. And if we want to combine democracy with the nation state, then it is bye-bye deep globalization" (Rodrik, 2011: 200). The logic of deep globalisation necessarily implies a weakening or transformation of national policies; the role of the state is reduced to that of the general controller of compliance with some basic conditions. Indeed, the state constitutes a hindrance to deep globalisation and must therefore be curtailed – this is perfectly in line with Rodrik's thesis. Now, what happens if nation-states are reduced and democracy maintained globally? A world democratic order is sought that Rodrik calls the 'global governance option' (Rodrik, 2011: 202). This mode of governance can be imagined as a 'global federalism' based on the worldwide replica of the US model or a milder form of association, such as the EU. Rodrik's thesis is that in this situation, that is, maintaining democracy and deep globalization by reducing nation-states would inevitably lead to a weakening of democracy itself. The reason for such weakening is twofold: a) state institutions would no longer be able to protect democracy, b) the logic of deep globalization is by essence 'disruptive' to democracy in the sense that it tends to deepen inequalities, while democracy tends to create equality. The handling of the trilemma is the subject of much debate. For Rodrik, there is a need to limit deep globalisation and restore the strength of nation-states. However, other econo-

mists argue that the solution must come through strengthening international rules.

The possible scenarios opened by the trilemma can be schematised as follows:

The problem that I want to raise is that we need all these elements *together* (GL + DE + SS) to develop a model of governance conceptualised by RI and TA.

In scenario 1, SS is needed because RI and TA implicitly refer to state sovereignty or international institutions' sovereignty (e.g. the UN or EU and its regulatory context) to regulate technological innovation. This aspect is evident in the literature, as we saw earlier. TA and RI are about anticipating moral choices and taking responsibility for future developments in technology that may affect future generations. In this regard, RI and TA always have a normative background and political objectives. This double normative dimension relates to the public dimension and therefore to the normative sphere of states, or international organisations.

The connection between TA and RI and the normative sphere of states or international organizations becomes particularly clear in instances of TA de-institutionalisation. De-institutionalisation refers to the process where formal structures or established practices of conducting TA within governmental or institutional frameworks become weakened or dismantled. The examples given from the United States and Belgium indicate situations where the formal mechanisms or organizations responsible for evaluating and guiding technological innovation in a responsible manner have been reduced or removed. This process underscores the political and normative dimensions of TA, as the presence or absence of such institutions reflects broader decisions and values within societies about how technology should be governed and for whose benefit (see Delvenne and Parotte, 2018; Van Est and Brom, 2012).

In scenario 2, we need DE because RRI and TA are intrinsically connected to representative democracy and its deliberative rationality. This aspect is evident in Von Schomberg's (2011) study in which RRI was demonstrated to be intrinsically connected to the European decision-making and regulatory structure. As observed earlier, RI and TA are expressions of participatory democracy and a deliberative rationality that is inherently democratic: "With regard to the ethical aspect, deliberation is a requisite in cases of conflict, disagreement or uncertainty, as, for example, when moral intuitions are shaken by new problems, typically surrounding emerging or controversial technologies or when ongoing research brings uncertainty with it" (Reber, 2017: 2). The deep connection between democracy and TA is evident in Grunwald's (2019) work, according to which TA is inherently related with deliberative democracy. According to Grunwald, TA is the expression of the pragmatist and democratic rationality theorised by John Dewey and Jurgen Harbermas. "Technology assessment is not value-neutral but is bound to values of human rights, rights of citizens, division of power, and other crucial issues of a democratic and inclusive society" (Grunwald, 2019: 97). This also means that "among the roots of TA was and still is the concern that scientific and technological advances do not per se support democracy" (Grunwald, 2019).

In scenario 3, we need GL because technological innovation and the free market are intrinsically connected.[8] However, analysing the ways that this connection can be achieved is problematic; the literature is enormous, presenting many theories and theses. Determining the roles of the state and market in innovation is still an open problem (see Mazzucato, 2017).

Going back to my main point, I limit myself to maintaining that certain levels of competition, capital, and business circulation are crucial to

Table 2. Overview of the proposed reformulation of Rodrik's trilemma

Scenario	Gains	Losses
1	+ GL + DE	- SS
2	+ SS + GL	- DE
3	+ DE + SS	- GL

GL, globalisation; DE, democracy; SS, state sovereignty.

obtain technological innovation. The essence of this thesis and the problem lies in the concept of 'a certain level'. To regulate technological innovation, the free market must be regulated; otherwise, the risks to society could be enormous. However, regulating the free market requires both democracy and state sovereignty, assuming that state sovereignty without democracy does not interest us. Nonetheless, this is exactly what the trilemma prevents us from doing, and this is also confirmed by the impossibility to build a global governance capable of regulating the markets (see Rodrik, 2011: 67–77).

An objector could reply to this last point by stating that the solution of the trilemma could be to promote moderate growth, that is, a more flexible and light form of globalisation, to keep the three aspects together (DE, GL, and SS). However, this argument does not work. The presence of GESs is an essential feature of deep globalisation. Owing to their nature, these engineering systems inevitably tend to devalue SS and DE; as mentioned earlier, they are transnational and often managed by private companies that have large capitals and are much more dynamic than states. In a world based on the presence and interaction between GESs, SS and DE inevitably tend to decrease. This does not mean that GESs are undemocratic. Instead, this means that they impose a re-conceptualisation of our democratic systems and national sovereignty.

Taking stock of what has been said, I have shown that all three elements (GL + DE + SS) are necessary to develop the model of governance conceptualised by RI and TA. However, these elements cannot be kept together.

Conclusions and future research direction

Based on this argument, I propose two hypotheses. The first is that the design of global engineering systems might be the key to reconciling the three facets of Rodrik's trilemma. Thus, technology should not be viewed merely as a force secondary to economics or politics. Instead, it is better understood as an independent, third force that can be harnessed to counterbalance the first two. The question then is: 'How might we structure our engineering systems to help shape a new world order that ensures freedom, prosperity, independence, and justice for the maximum number of people?' Clearly, this is a query that future research endeavours must explore further.

However, merely pointing out ethical dilemmas and design remedies is an oversimplification. My second hypothesis is that RI and TA demand a profound philosophical re-foundation. This is not just about adapting existing theories but also about pioneering new paths of understanding. This exploratory journey seeks to redefine the essence of RI and TA, examining them through the unique vantage point of the Anthropocene.

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Notes

1 In this paper, I follow Kuhn (1970) in the use of the term 'paradigm'. According to Kuhn, a paradigm encompasses the collective practices that characterize a scientific discipline at a given point in time. It directs the course of research and practice within the field, delineating what constitutes valid research and defining the parameters for scientific inquiry. A paradigm represents the scientific achievements that are broadly acknowledged and serve as benchmarks, offering model problems and solutions for a community of practitioners. It includes not only the prevailing scientific theories but also the methodologies, norms, and standards that are collectively endorsed by the scientific community, guiding their research activities and the interpretation of data. When a paradigm undergoes a crisis or shift, it heralds a profound transformation in the foundational principles and practices of the discipline, a phenomenon Kuhn describes as a scientific revolution. In this paper, I consider LWO as a paradigm for thinking about and developing international relations.

2 The study of infrastructures and expansive technological systems is a theme that, despite its long-standing presence, experienced a phase of diminished prominence within the STS field before witnessing a resurgence. Thomas Hughes's work stands as a seminal contribution to this domain (Hughes, 1983). The 1980s saw considerable engagement with these themes, notably through the anthology edited by Bijker and others in 1987 (Bijker et al., 1987). Susan Leigh Star significantly advanced the discourse on infrastructure through her detailed enumeration of its components, establishing a key resource still referenced today (Star, 1999). The importance of considering global systems is underscored by the pioneering efforts of Paul N. Edwards, with his 2010 book marking a cornerstone (Edwards, 2010). In recent years, a notable segment of the STS community has increasingly focused on the concept of infrastructure, as evidenced by works like Silvast et al. (2013), Monteiro et al. (2014), and Karasti et al. (2016).

3 In my view, the category of socio-technical systems includes that of engineering systems and global engineering systems. Both are increasingly complex socio-technical systems. Additionally, there is a difference between global engineering systems and technological networks (Newman, 2018). Many global engineering systems have the structure of a network (e.g., the internet, electrical or gas networks, transportation networks). However, there is a difference between the two concepts, those of technological network and global engineering system. This difference, in my opinion, lies in the relationship with law and political power. Global engineering systems have a strongly political dimension, in the sense that they redefine the legal and political dimension and have a certain control over this sphere (e.g., the European energy network is composed of many actors, such as nuclear, coal-fired plants, gas, and renewable systems, and all together impose political decisions that are independent of national governments). The technological network does not; it is a conceptual and physical architecture but lacks political value. However, this claim could be contested by using Latour (2005).

4 For each term analyzed, I calculated its frequency by dividing the number of occurrences by the total number of papers in the reference group (either RI or TA). I then multiplied the result by 100 to express it as a percentage. This calculation tells us, on average, how many times the term appears per paper, expressed as a percentage of 1 occurrence per paper. It's a measure of the term's frequency relative to the number of papers, not the number of times it appears in all papers combined.

5 Is it possible to link the LWO crisis to the vagueness of the RRI conceptual statute? "RI and particularly RRI are discourses in the making and are interpretively flexible. It is important to recognize that what responsible innovation purports to be is yet to be settled. These are discourses that are in an active process of discursive translation that is yet to stabilize" (Owen and Pansera, 2019: x).

6 The early history of the Internet traces back to the late 1960s and early 1970s, born from the need for a robust, fault-tolerant communication system during the Cold War era. The Advanced Research Projects Agency Network (ARPANET), funded by the U.S. Department of Defense, was the first operational packet-switching network and is widely considered the precursor to the Internet. Initially designed to allow multiple computers to communicate on a single network, ARPANET's first successful message was sent between computers at UCLA and Stanford Research Institute on October 29, 1969. This groundbreaking network laid the foundation for the development of protocols that would eventually enable the connection of multiple networks into an interconnected network of networks—the Internet. Over time, the introduction of the Transmission Control Protocol/Internet Protocol (TCP/IP) in the early 1980s facilitated this expansion, marking the beginning of the modern Internet era. See Castells (1996), Hafner and Lyon (1998), Abbate (1999), Stokel-Walker (2023).

7 Building on Morton's (2013) perspective, I identified 16 July 1945 as the date of the Trinity test and the commencement of the Anthropocene. However, this epoch's onset is debatable, with others attributing its start to the onset of the Industrial Revolution.

8 Why are they connected, and how? In his seminal book, *The Free-Market Innovation Machine*, Baumol (2002) explored the mechanisms through which free-market economies foster innovation and economic growth. Drawing on a wealth of historical and economic data, Baumol demonstrated that capitalism and competitive markets are unrivaled in their ability to stimulate relentless innovation and hence unprecedented economic growth.

Steered or Guided by Numbers? How Climate and Energy Policymakers Domesticate Quantitative Information

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Abstract

Concepts like 'the metric society' and 'the tyranny of metrics' suggest that quantitative information increasingly shapes and steers policy and governance. This paper engages critically with such assumptions by using domestication theory to analyse how Norwegian climate and energy policy actors make sense of, assemble, and employ numeric information. Through analysis of interviews with politicians and public employees working with climate and energy policies in the Norwegian government administration, we identified three main categories of narratives of domesticating quantitative information: (1) Numeric engagements, (2) Uncertainty, and (3) Pragmatic information management. Employees in the administration articulated either of the two first categories, while politicians and political advisors performed the third. All interviewees highlighted the need for cautious and reflexive approaches to numeric information rather than enthusiastically embracing such information. In their decision-making, the policymakers appeared to be guided by numbers rather than steered by them.

Keywords: Energy, Climate, Policymaking, Quantification, Numeric information, Domestication

Introduction: Numeric governance

Numbers may be employed in governance and policymaking for many purposes, such as identifying directions of preferred social development, benchmarking such developments, and articulating specific targets. Policy documents often provide extensive quantitative information as a basis for decisions. For example, the latest Norwegian White Paper on climate mitigation (Ministry of

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Climate and Environment, 2021) contains 583 figures, on average, about 3 per page of text. The document uses descriptive statistics, modeling, and scenario work to describe the present situation regarding climate gas emissions and energy production and consumption and to present targets for reducing emissions, enhancing energy efficiency, and increasing the provision of renewable energy. Based on interviews, this paper analyses how Norwegian policymakers working with energy and climate issues account for their appropriation and use of such numeric information.

Many scholars have argued that numeric information dominates policymaking and shapes the conception of politics. For example, Blastland and Dilnot (2008: 1) claim that "Numbers saturate the news, politics, life. For good or ill, they are today's pre-eminent public language – and those who speak it rule". A widespread argument is that quantification practices have become too dominant and should be critically examined (e.g., Porter, 1995; Power, 1997; Muller, 2018; Mau, 2019; Rose, 1991; Strathern, 2000; Sætnan et al., 2011). Implicit in such claims is the belief that numbers have epistemic authority that may lead to uncritical employment in policymaking.

Asdal (2008, 2011) argues that statistics has been a central political technology in Norwegian debates about pollution because policymakers believe statistics provide relatively unbiased information. Thus, Norwegian politicians deciding on pollution regulations have relied mainly on quantification as an instrument of governance because, as Asdal concludes, numbers are associated with authority. Many other scholars observe how quantified information is often used to substantiate political choices when policymakers claim that they base decisions on information they consider as objective as possible due to assumptions about how quantified information is made (Porter, 1995; Power, 1997; 2003; Strathern, 2000). Experts are expected to produce numeric information in standardised ways, adhering to rules that are believed to constrain the influence of personal and subjective views. Porter refers to this practice as the pursuit of mechanical objectivity, noticing how such quantification efforts replace trust in people with trust in numbers. Desrosières (1998) also highlights the importance of numeric targets and the pervasive role of calculative practices in modern political culture. In his words, "they [the numbers] are inscribed in routinised practices that, by providing a stable and widely accepted language to give voice to the debate, help to establish the reality of the picture described" (Desrosières, 1998: 1).

Grek and Rinne (2011: 19) exemplify the claimed importance of numbers when they observe that the EU's "rapid change of policy discourses and practices" has moved from constructing a "European culture to a Europe governed by numbers". Other scholars have argued that the domain of governance has become numerically constituted and delineated and that counting is a way to define a problem and make it amendable to governmental action (Baele et al., 2017; Rose, 1991). Thus, from this perspective, governance is co-produced with numerical, policy-relevant information. The outcome is what Power (1997) calls 'the audit society', where public administration must convert 'everything' into numbers that they may use as a basis for policy decisions to make them auditable.

Thus, this line of research considers numeric measurements and estimates to be used to assess social developments and compare practices and situations. Several scholars argue that the consequences are problematic. Power (1997) and Muller (2018) claim that auditing tends to have unintended, dysfunctional effects on audited practices. Muller argues, "Unfortunately, the issue is not one of metrics versus judgment, but metrics as informing judgment, which includes knowing how much weight to give to metrics, recognising their characteristic distortions, and appreciating what can't be measured" (Muller, 2018: 183).

However, we cannot assess the effects of auditing and using quantitative information in policymaking primarily from the calculative practices involved. Instead, the features of such effects are an empirical issue. Moreover, we consider policymaking as a process rather than a particular decision. By investigating policymakers' use of quantitative information when dealing with energy and climate issues, we aim to contribute to understanding the complex processes of developing transition policies related to climate and energy. Köhler et al. (2019) and Sovacool

et al. (2020) have identified such knowledge as a pertinent need in sustainability transition research. The importance of investigating the use of numbers in sustainability transition policies is further indicated in the Norwegian context by the apparent inconsistency between the abovementioned White paper on climate mitigation and the Parliament's Standing Committee on Energy and the Environment's recommendations to the Parliament regarding the White paper (Innst. 325 S (2020-2021), Ch. 4). While the first, as we have seen, abounds with numeric information, the latter are nearly without any numbers. It mentions only three numeric goals among 148 recommendations. Why this striking difference?

Understanding the quantitative practices of policymaking

The increasing amount of quantitative information provided in policy contexts reflects the rise of the profession of economists as policy advisors and policymakers, although their role varies considerably across nations (Fourcade, 2009) and may even be mediated by local circumstances (Hirschman and Berman, 2914). In Norway, economists exercise strong discursive and practical influence on climate and energy policy (Sørensen, 2015). A simple measure of their impact in this policy area is the observation that the Ministry of Oil and Energy employs more economists than the Ministry of Finance. Cost-benefit analysis prevails, and concepts from economics are considered essential as a kind of pidgin used to communicate across professional assessments (Jomisko, 2015; Øvstebø Tvedten, 2022).

During the 1980s, many OECD countries moved towards the practice of so-called New Public Management (NPM), a reform where public management practices shifted towards 'accountingisation' (Power and Laughlin, 1992: 133). This reform meant the introduction of ever-more detailed cost categories into areas where cost previously was aggregated, pooled, or undefined (Hood, 1995). Another essential aspect of NPM is the emphasis on rankings and change indicators. This practice requires quantification of relevant governance features.

Often, numbers are granted a greater authority than more qualitative forms of knowledge (Espeland and Yung, 2019). Espeland and Stevens (2008: 414) describe numbers as "a key mechanism for the simplifying, classifying, comparing, and evaluating that is at the heart of disciplinary power". Numbers are often perceived as transparent, secure, well-funded, and credible (Demortain, 2019). When something is quantified, it appears to create trust, be easy to relate to, and provide a clear basis for action, although this may result from the considerable work of the involved actors (Daston and Galison, 1992; Desrosières, 1998; Porter, 1995; Power, 1997).

Furthermore, quantification is often presented as apolitical and persuasive (Bruno et al., 2016). Supiot (2015) claims that numbers have replaced law as the leading government technology. Rottenburg and Merry (2015: 7) argue that numeric representation in governance, first of all, consists of methodologies to achieve two primary political purposes: (1) to simplify complexity in order to come to a conclusion and be able to collaborate or act in the name of a collective, and, in doing so, (2) to demonstrate adherence to public responsibility and absence of personal or group bias. These attributes may make numbers attractive and enchanting to governance despite widespread academic critique that current quantification practices involve questionable gathering, interpretation, and use of quantitative information (Sætnan et al., 2011; Bruno et al., 2016; Mennicken and Espeland, 2019; Berman and Hirschman, 2018).

The reliance on numbers may shape governance practices. Baele et al. (2017) observe three distinct shaping features: persuasion, (de)politicisation, and standardisation. Such effects presume trust in, and authority of, quantitative information. Similarly, Muller (2018: 17-18) introduces the 'metric fixation' concept, which describes the increasing demand for performance measurements and output documentation. On the other hand, politicians may be accused of numeric incompetence (Blastland and Dilnot, 2008).

Moreover, policymakers may exercise considerable discretion in their use of numeric information. Mügge (2020: 14) argues that "Politicians are no hostages to economic data". Some previous

research supports this. In the Norwegian context, Næsje (2002) found that when the Parliament decided on a system for heat pump subsidies, the politicians dismissed economic calculations in favour of moral arguments. Deringer (2018), on the other hand, describes the authority of numbers as coming from the turmoil of politics and not from efforts to find objective truths that transcend politics.

Thus, there are diverging views about the actual impact of numeric information on policymaking. Some see numeric competence and the strategic interests of policymakers playing a role. Still, much previous research on quantification is influenced by post-Foucauldian approaches that emphasise the performativity or the discursive strength of numbers. We wanted to study practices and sensemaking of quantification in climate and energy policymaking without prior assumptions regarding the performativity of numbers. Thus, we wanted a theoretical approach that gave policymakers agency in their relationship with numeric information. These considerations led us to employ domestication theory (Berker et al., 2006; Hartman, 2023). This approach replaces linear thinking about effects and perceives users of scientific knowledge and information as actively making choices in their appropriation processes (Sørensen, Aune and Hatling, 2000). Domestication theory has been used to analyse the use of a wide variety of knowledge and technologies, including policymaking but, to a lesser degree, the employment of quantitative information (Ask and Sørensen, 2019; Haddon, 2011; Hartmann, 2023; Lagesen 2021; Sørensen et al., 2000; Sørensen, 2006). We see domestication theory as an appropriate tool of analysis since it invites us to study the impact of quantitative information on policymaking in a manner that highlights the agency of policymakers without making assumptions about the decisive forcefulness of numbers.

Instead, with domestication theory, we assume the processes of applying numeric information to policymaking to be situated, meaning that the issues at hand shape its application and interpretation. Further, the availability of alternative sources of information and the interaction between policymakers must be considered. Thus, emphasising situatedness invites observations of contingent outcomes and provides a generative framework to explore accounts of the extent to which and how quantification shapes and is entangled in climate and energy policy.

Drawing on actor-network theory (Latour, 2005), domestication may be described as the assembling of human and non-human elements, resulting in heterogeneous assemblages of practices, sensemaking, and cognitive aspects. This process entails making links to, for example, other artefacts, other practices, alternative sources of information, and other people, as well as engaging in interpretative and organisational efforts (Sørensen, 2006). Thus, when we apply domestication theory in our analysis, we implicitly inspired by actor-network theory.

Consequently, in this paper, we ask how policymakers in the climate and energy area describe (1) their use of numeric information, (2) the meaning they attribute to numbers assumed to be relevant for policymaking, (3) how they access numeric and non-numeric sources of information, and (4) their understanding and assessment of such information. We also consider the possibility that domestication is unsuccessful because numeric information is misunderstood or discarded. The paper's primary concern is to explore what place numeric information has in assembling climate and energy policy decisions.

Method

To study how policymakers addressing climate and energy issues domesticate numeric information, we chose a qualitative approach mainly based on interviews but supplemented with analysis of a few reports produced in the policymaking processes. (We refer to them when they are used). The interviews provided data about how policymakers reasoned around their engagement with quantified input, assessed quantitative information compared to qualitative alternatives, received and gathered information, and how issues and context might influence policymaking. We did not ask them about specific cases, but often, the interviewees would exemplify their practices by referring to particular decisions. A few mentioned the Norwegian White Paper on climate mitigation (Ministry of Climate and Environment,

2021), but the examples varied greatly. Thus, we could not focus on a single policy issue. We used documents, mainly reports made by the Standing Committee on Energy and the Environment to the Parliament, as a backdrop to the analysis of the interviews.

We define policymakers to be politicians and their advisors, but we have also included employees in ministries and directorates in this category. The latter group may not make the final decisions, but they provide suggestions for policies, background information, and assessments of the effects of policy measures. The first author conducted 20 semi-structured, in-depth interviews with these groups of policymakers. She interviewed six politicians. One was a former Minister of Oil and Energy, and five were Members of Parliament (MP) with a seat in the Standing Committee of Energy and the Environment. These five constituted almost 1/3 of the committee. Three political advisors to MPs were also interviewed. The remaining 11 interviewees worked in the Ministries of Oil and Energy, Climate and Environment, and their subordinate directorates. The interviewed politicians represented The Green Party, The Progress Party, The Conservative Party, The Christian Democratic Party, The Socialist Left Party, The Labour Party, and The Liberal Party, thus covering the whole spectrum of Norwegian politics.

The context of the study is Norway, which is often described as an 'energy nation' by policymakers due to the great economic importance of energy production. Norway is a significant oil exporter and the world's third-largest exporter of natural gas. Hydroelectric power is the backbone of the country's energy-intensive industry (Ryghaug and Skjølsvold, 2013). Hence, energy issues and climate mitigation get much political attention.

The first author undertook the interviews between June 2016 and February 2018. Fourteen interviews were done in person, lasting 45-90 minutes, while the remaining six were conducted by telephone, with calls lasting between 25 and 45 minutes. Interviewing policymakers raises challenges with access, mainly because they are busy and usually must be reached through a secretary (Undheim, 2003). Occasionally, this made interviewing by telephone the only option. Telephone interviews have been considered as not providing 'sufficiently rich' data. Other well-known concerns are the lack of non-verbal communication and the possibility of capturing diversity (Tjora, 2021). Still, we found that the telephone interviews provided informative and expressive conversations, in line with Christmann (2009).

The interviews followed a flexible interview guide. We asked the interviewees what kind of knowledge they considered to have the most impact and was most persuasive, including how they considered, understood, assessed, and used numeric information. Further, we inquired about their sources of information and to what extent they trusted the sources. All interviews were recorded and later transcribed verbatim by the first author. The authors have translated the quotes used in the paper into English. All interviewees have been anonymised and are referred to by abbreviations. We call the politicians P1-P6, the political advisors PA1-PA3, the employees in ministries M1-M3, and those working in directorates D1-D8.

Given the pervasive use of numbers in policy documents addressing these issues and the relative transparency of governance in Norway, we expected the interviewees to be able and willing to reflect on the role of quantification in their policymaking. This expectation was met. The interviewees were quite open about their practices related to policymaking, including how they appropriated and assessed both quantitative and qualitative information. They described to us the formal system of provision of information and the supplementary informal ones.

When analysing the interviews, we found considerable diversity among the interviewees in their accounts of practices, forms of sensemaking, and learning strategies of numeric information. However, after closer examination, similarities appeared. We used thematic narrative analysis, where content is the exclusive focus, and the primary attention is directed at *what* is said rather than how and to whom (Riessman, 2008). We concentrated on what was said about quantification and the domestication of numeric information, sorting this by categorising statements into the three domestication aspects: practice, sense-

making, and cognitive issues. We identified three main narratives regarding the domestication of quantitative information. In the next section, we briefly introduce the three narrative categories. We then explain each of them in some detail before making some concluding remarks on how policymakers in the energy and climate field domesticate numeric information when crafting energy transition policies.

This article presents a case study of how quantitative information is domesticated in the context of climate and energy policymaking in Norway. This context is specific, so may there be broader implications? First, the numeric information provided in the relevant Norwegian policy documents appears to fall within the same categories we find with the IEA and many other countries; thus, it is not specific to Norway. Moreover, the interviewees repeatedly mentioned the IEA and the EU as essential sources of information, and some also said they were closely following developments in other countries. Second, several of the interviewed politicians had experience from other policymaking areas. The only area they described as different from climate and energy concerning the role of numeric information was financial policy, which they considered much more quantified. Still, any generalisation of our findings must be done carefully, but we assume the processes may also be observed in other contexts.

Narratives about the domestication of numeric information in climate and energy policymaking

The interviewees described climate and energy policymaking as situated in a comprehensive and complex information ecology characterised by rich formal and informal input flows. They had to navigate these flows, but there were few complaints besides mentions of time constraints. Numeric information appeared in writing or orally. The interviewees did not emphasise such differences in material form, but written sources were the most frequently mentioned. They also commonly referred to qualitative forms of information. When we asked about their assessment of the information quality, a striking feature was a high level of trust in both numbers and narratives. This observation reflects that trust is an inherent quality of Norwegian governance and politics.

The exchange of information between the groups of actors we interviewed was shaped by the formal structure of their information ecology, with the Standing Committee of Energy and the Environment (SCEE) as the central climate and energy policymaking arena. The committee was the endpoint of the formal information flow. Its task is to provide recommendations to the Parliament for final policy decisions regarding energy and the environment, which includes climate issues. Some recommendations may be unanimous, while others are supported by a majority or a minority of the committee.

The committee has two primary sources of formal input to its deliberations. One is proposals from Members of Parliament. The other and the most prominent is the Government, chiefly the Ministry of Climate and Environment and the Ministry of Oil and Gas. They supply Green papers, White papers, legal propositions, and other printed material. In addition, the committee members said they collected information independent of the administration, for example, through visits to relevant companies, research institutes, and universities.

The main tasks of the interviewed ministry employees were to collect and review information, contribute to White papers and reports to politicians, and communicate with politicians and the public. They collected information from many sources. They received or asked for input from the subordinate directorates while commissioning consulting companies and acquiring information from other external actors, such as Statistics Norway, the Research Council of Norway, IEA, research institutes, and environmental non-governmental organisations (ENGOs).

The interviewees from the directorates also collected and reviewed information, but many also engaged in calculations, often using economic or techno-economic models. Thus, they worked intimately with numeric material, more than the ministry employees. However, their primary sources of input were more limited. Statistics Norway was the leading supplier, but they also collaborated with research institutes and commissioned consulting companies. Occasionally, they

collected data themselves. The directorates served the two ministries mainly with quantitative information.

As previously noticed, research about the role of numbers in the governance of modern societies suggests that a vital aim is to invoke trust (e.g., Porter, 1995; Daston and Galison, 1992) but also that there are good reasons to approach the role of quantification in government critically. Further, this research emphasises how processes of quantification have increasingly become pervasive. The quantification of climate and energy issues in the Norwegian context is striking, easily verified from any White or Green paper addressing such concerns. The pervasiveness of quantification was also evident from the interviewees' accounts. They mentioned a variety of numeric climate and energy policymaking inputs. These inputs included descriptions of the present situation or historical developments in energy production and CO_2 emissions, model-based predictions of future changes, output from climate and weather models, cost assessments of policy instruments such as incentives, and calculations of the impacts of policy measures. Targets could also be numeric (Jørgensen and Sørensen, 2022).

In particular, the interviewees from the directorates accentuated quantification, which they considered vital. For example, D1 explained the importance of being exact.

> When we advise the cabinet minister and the Ministry, numbers and facts are essential because they [the Ministry] must have clear documentation when discussing with other ministries and balancing the concerns regarding oil and energy policy, financial policy, or other stuff.

Still, numbers did not reign supreme. The directorates and ministries interviewees said that politicians often needed stories when explaining policies. In addition, their understanding of how policy instruments worked required other forms of knowledge.

> Numbers are interesting in themselves … but much of what we collect is knowledge about how companies' decisions look, how they affect the diverse ways of organising policy instruments, how this influences the incentives (…). [I]t is as much that 'how question' we are interested in.

Similarly, M3 reflected that:

> [O]f course, we are concerned with numbers … the whole building is engaged with describing the effects of various forms of policy, and that does not have to be only numbers. It may be numbers but also descriptions of mechanisms and relationships, which may be pretty complex within climate politics.

In addition, the interviewees from the ministries and directorates explained that politicians might ask for stories they could use for more effective communication. D6 added that:

> [W]hen you move upwards [in the decision-making system], it is – like, what did I want to say – more general views than numbers that determine the decisions.

While they spent much time and energy dealing with quantitative information and appreciated the quantification of climate and energy issues, these interviewees had a level-headed relationship with the numbers they provided. They also valued qualitative knowledge and were careful not to reduce its importance. This moderation was expressed in two categories of narratives. Narrative 1, which we call *Numerical engagements*, was a mundane report about quantitative practices and the meaning given to numbers. Narrative 2 we call *Uncertainty*. It was an account of risks concerning the accuracy of numbers, how their sensemaking led to concerns about uncertainties, and their practices in dealing with this. Interviewees from the directorates offered Narrative 1, while the interviewees from the two ministries and some from the directorates articulated Narrative 2. The two narratives were not mutually exclusive, meaning that some interviewees offered both.

The interviewed politicians and political advisors articulated a third narrative, *Pragmatic information management*. This narrative described a practical domestication of information, emphasising the context of decision-making practices, the relevance of the available information, and the need to employ sources beyond the formal input

from the two ministries and the three directorates. When inquired about the impact of numbers and statistics on policymaking, P2 plainly stated, "I've yet to experience that it is [such facts] that tilt a case [political decisions]."

Moreover, the recommendations from the SCEE and the subsequent decisions that the Parliament makes are usually verbal and non-numeric. If we return to the previously mentioned Climate mitigation plan (Ministry of Climate and the Environment 2021), typical decisions were 'The Parliament asks the government to determine that increased taxation of Norwegian production of meat should not be implemented as a part of the climate policy' (Decision 791) and 'The Parliament asks the government to ensure the development of a general infrastructure for zero- and low-emission vehicles' (Decision 792).[1]

This writing of recommendations does not imply that the politicians considered quantitative information unimportant. However, we found the impact of numeric information challenging to trace through the series of official documents. When we compare the White paper presenting the Climate mitigation plan, the report about the plan made by the Standing Committee, and the recommendations in the report (Innst. 325 S (2020-2021), Ch. 4), we see a radical decline in the use of quantitative information from a lot to a little to nothing. This reduction could mean that numbers have been transformed into qualitative statements, but the interviewees were unclear to what extent this happened. However, the decline resonates well with the pervasive pragmatism of Narrative 3. Also, Narratives 1 and 2 had, as we shall see, a pragmatic flavour but less pervasive and prominent than Narrative 3.

In the following, we describe the three narratives in greater detail. We begin with Numerical engagements.

Presenting the narratives

Narrative 1: Numerical engagements

The accounts of the domestication of quantitative information that constituted Narrative 1 were shaped by the prevailing calculative practices that reflected the profound quantification of the climate and energy area. This quantification reflected an audit culture where targets tended to be formulated quantitatively, and achievements were measured through indicators and statistics (cf. Jørgensen and Sørensen, 2022). The calculation practices varied but could include the use of models, the collection and reviewing of data, and the communication of results. D4 described his and colleagues' work as 'knowledge refinement', involving synthesis, assessment of the knowledge status, and policy advice.

All the interviewees from the directorates had higher education, mainly with degrees in economics and engineering. Thus, they were trained in the use of numbers. Their task was to provide relevant and reliable information about climate and energy issues to the policymaking process, such as statistical overviews of CO_2 emissions and the production of energy, projections of future energy demand, and assessments of relevant policy instruments, for example, through cost-benefit analysis. Their role could also be to inform about the ongoing work of and recommendations from The Intergovernmental Panel on Climate Change (IPCC). A primary task was the quantitative assessment of target attainment.

The processes of sensemaking reflected the pervasive engagement with numeric information. Most interviewees contributing to Narrative 1 described their sensemaking as mundane and focused on the interpretation and trustworthiness of the information. D3 referred to her directorate's communication strategy. "If you get an enquiry from the news media, you need to be very certain before saying anything. So, a culture of caution has developed." D7 related that what is good data, "ultimately, that is a discretionary assessment." D8 was one of the few who made a general statement describing numbers as necessary and valuable.

When saying this, D8 referred to his and his colleagues' practices related to developing and managing programmes to support the development of new renewable energy and energy efficiency, as well as assessing and reporting the achievements of the programmes. The Ministry "owning" the directorate preferred to set numeric targets. D8 attributed this to their assumed disciplining effect for achieving results. "Politicians and the Ministry would like us to produce results.

And it happens to be like this in the bureaucracy. Results that can be measured can be presented as facts". Thus, he meant that politicians preferred figures over more qualitative information due to the assumed precision, order, and stability of the former. This preference shaped the directorate's domestication of numeric information, making quantification and calculation central practices. For example, numeric targets required the production of adequate indicators of efforts and outcomes to allow auditing, helping them to observe how close they were to reaching their targets. As D8 put it, "Numbers are important; they give us a sense of speed".

D7 also emphasised the importance of quantifying targets as much as possible but assessed by a combination of qualitative and quantitative indicators. This auditing practice was the basis of negotiations with the Ministry and embedded in the current energy policy. He concluded that this situation exemplified that numeric information "if not steering policy, so at least it's considered in the policy development". Further, D7 observed the directorate's obligation to perform parts of the energy policy. One aim was to make the present use of subsidies superfluous. Such qualitative goals tended to result in quantitative targets. "In reality, we are supposed to reduce market barriers. And that is a qualitative goal, but to have control and the proper focus, one tends to make related quantitative targets."

Thus, qualitative goals were pursued through metrification. Metrification describes the process where qualitative judgement is replaced by numbers (Lorenz, 2014; Saltelli, 2020). However, D8 pointed to a counteracting tendency. "There is a development [in the directorate] where we try to understand the world with other kinds of data than just quantitative data (…). Those who are the target groups of our programmes are actors in some context, in a market, and then you want to try to understand, not just counting but understanding what drives these actors."

He added that much of their policymaking was far more complicated than could be described using numeric information only. "Even if you've got numeric information and you make forecasts when you've access to time series that point in a specific direction and predict a future, things will happen and change these forecasts very often. If there's one thing economists need to understand, or at least should understand, it's that history shows that predicting the future is very difficult." Thus, the sensemaking resulted in some caution regarding the quality and accuracy of numeric information. For example, several interviewees complained about surveys with poor data selection, small samples, and too fragmented presentation.

An instrumental relationship to numeric information was widespread. The interviewees described numbers as an essential ingredient of their work, but the cautious domestication with a critical view of trustworthiness displayed little affective engagement. Only a few interviewees provided affective responses. For example, D5 emphasised that ambitious targets made him, and his colleagues work hard: "Then you work in a way to achieve it [the target], and sometimes we don't make it, but if you set a significantly lower target that's easier to reach, you only slow down the pace".

Affect was also evident from D5's comment that one should not "underestimate the importance of captivating numbers". Ambitious targets were considered appealing and to inspire people to keep up the work pace, trying to drive them. Thus, to some, numeric targets could be effective motivators. They articulated both an instrumental and affective relationship to numbers but no strong affection.

Regarding the cognitive aspect of domestication, in Narrative 1, there was little mention of the learning processes related to numeric information beyond the information gathering. However, the widespread critical acknowledgement of inaccuracies indicated that this aspect of domestication also included reservations regarding its importance and trustworthiness. Narrative 1 included statements suggesting a nuanced understanding of numbers' limited generalisability and uncertainty. Numeric targets were decided top-down, and the narrative reflected a felt need to identify with them despite statements suggesting a more cautious sensemaking, emphasising the uncertainties of some of the estimated quantitative measures.

The information collection was essential in cognitive domestication, as articulated in Narrative 1. The directorates used many sources. Statistics Norway appeared as an essential supplier, but research institutes and consulting companies were frequently approached. When inquired about quality criteria, the interviewees tended to be vague, but some sources were considered more trustworthy and relevant than others. The Norwegian research scene was described as small and surveyable. "We regularly use pretty much all of them" (D4). According to D5, "So you want to employ recognised institutions, I would say. You don't shop completely random numbers, no."

Narrative 2: Uncertainty

The Uncertainty narrative was partly present in the Numerical engagement narrative in the mention of inaccuracies. Still, it is worthy of a separate analysis since it articulates a distinct domestication of quantitative information. The primary practices described in this narrative were reliability assessments and communication with politicians and the public. These practices were closely related to the reviewing and assembling of numeric information. The Uncertainty narrative were articulated by interviewees from the two ministries and the directorates, often in tandem with Numerical engagement narratives.

The emphasis on uncertainty was sometimes related to an uneasiness about the persuasive quality of numbers and the simplifications that often occurred when such information moved upwards in the system. D2 explained that "no matter how much we write about the uncertainty of [our analysis], one risks that it disappears a bit when it is filtered upwards, and one shall render the short version." Similarly, M1 worried that numbers would be taken at face value and used uncritically. She said quantitative information was often employed without reading the reservations and understanding the calculations' underlying assumptions:

> "(I)t's very attractive to be able to quantify stuff. So then …. we have a number, but it is uncertain (…). So that is the challenge with numbers, that they quickly live their own lives. I guess it is a human trait – that we love numbers. So, regardless of how much you say about how uncertain it is, it does not quite go all the way in."

D6 added to the Uncertainty narrative by reflecting on the dangers of thinking that some people believed they could find exact answers:

> "[I]n any case, when one engages in looking forward, there is a considerable uncertainty, so it is just knowing that it is uncertain, and how uncertain it is, that is vital (…). You may readily use the exact number, but one should, like, be at least as concerned about how large that uncertainty is (…). But many are looking for the one correct answer, and then you start shopping by the numbers and underestimate the uncertainty on the way because you are looking for the one correct answer and the arguments supporting it. And this is a general problem".

He also introduced another element, the costs related to obtaining high-quality data, and complained that too little time was spent on data collection:

> "Well, we certainly say that there is no problem. There are a lot of model calculations both regarding energy and climate, a lot of models, a lot of people who sit and calculate stuff, but all from the same poor data, which doesn't make it any better (…). But instrumentation, reporting, and validation of numbers cost a lot of money. Thus, it is often renounced."

Like D3, he was worried that uncertainties tended to be overlooked in the subsequent stages of policy development. Such ignoring resonated with M1's account. She invoked the Uncertainty narrative when she talked about providing input to politicians while striving to be precise without complicating the communication. She considered this challenging because of the complexity of the current climate and energy policy. M1 used IPCC reports as an example to emphasise that "uncertainty is one of the complexities, and it is very challenging when you are going to describe it in three sentences".

Thus, M1 made sense of numeric information as a necessary input to policymaking and a communication tool. She saw quantitative information as essential and persuasive numbers as an asset in

internal policy processes but was more hesitant regarding external audiences. "Well, numbers are valuable information, but the downside to numbers is that they often are perceived as much more correct than more qualitative information when this is not necessarily correct (…). So, it is, like, always a challenge to communicate the uncertainty around the figures". In this manner, M1 articulated an essential feature of Narrative 2, the understanding that numbers should be carefully interpreted by considering the assumption underlying calculations and the uncertainties involved.

M3 gave this emphasis on careful interpretation a particular twist, explaining that there could be disagreements about what kind of information could be considered facts. "Sometimes, we doubt the quality of the foundation of what is presented (…). It may happen that the Ministry disagrees with this or that factual basis, that we think that it doesn't maintain quality or that it in other ways is not good enough". Consequently, the ministries and the directorates could negotiate the interpretation of information.

In such ways, the Uncertainty narrative articulated an ambivalent view of numbers. Numeric information was vital but also uncertain. The quality of measurements and calculations could be challenged, and their implications negotiated. Moreover, the interviewees considered numbers persuasive, sometimes overly, which could lead to too much trust when such information moved upwards in the policymaking chain.

Regarding the cognitive aspect of domestication, there was much similarity between the Uncertainty narrative and the narrative of Numerical engagement. Information was collected from an impressively wide variety of sources, but not without differentiation. M1 said with an ironic twist, "Like I said, the IEA is always a useful source. If it is an occasional news service, it ranks much lower. Of course, environmental organisations, for example, also produce some quantitative information, and that is also something we read and relate to, but in a way, we would rather quote the IEA than Greenpeace".

Narrative 3: Pragmatic management of information

This narrative is based on the accounts of the politicians and the political advisors of how they domesticated numeric information or information more broadly. Their numeric practices were different from the other interviewees. They did not engage in calculations but reviewed quantitative and qualitative information to decide on policies and to explain them. The latter meant that communication was essential, above all in meetings with diverse groups of actors.

M3 mentioned several examples of policy practices, often related to the assessment of existing or planned policy instruments. One case was network tariffs, with which he had engaged on his initiative. "In my home county, this is a matter of great importance to very, very many. Here, I have needed to spend quite a lot of time to learn how the transmission network is connected to the distribution network, what lies behind existing efficiency measurements, and similar stuff". In this instance, he was working with hybrid information, some numeric, some more qualitative such as descriptions of technical and topographic matters or issues related to fairness. In another case, numbers were the predominant input. "Right now, we are engaged with the climate strategy for the sector that is not subject to [CO_2] quotas (…). In reality, it is a kind of budget, a climate budget for our country and how we shall reach the targets compared to the EU (…). Here, there are a lot of numbers. We use them."

The Standing Committee's prime activity was responding to documents from the Government. PA1 talked about the previously mentioned White paper on climate strategies (Ministry of Climate and the Environment 2021) as a current concern and observed that "this is a valuable document reference-wise for us because it describes a lot of facts about the status of the climate efforts (…). It already contains a lot of knowledge, but then we shall continue to work to bring our politics into this". He mentioned the party programme as essential, but it was also necessary to collect views externally by consulting with trade unions and ENGOs. The White paper provided numeric information, which they complemented with qualitative input. In Narrative 3, the domestication

of numbers was entangled in a comprehensive domestication of many categories of information, which was shaped by an understanding of what it meant to be a politician. As P2 explained, "To be a politician isn't about being a professional. It isn't a prerequisite to be into the details when you're a politician. What is important is to see the whole picture."

PA3 related that most of the information they collected was qualitative because "Numbers and statistics are often explained in White papers and such. They come with a lot of factual information, so then one has to supplement with the knowledge that one feels the White paper does not illuminate." He added that he preferred text over tables; he felt that text made it easier to see the more significant connections.

The cognitive aspect of domesticating information through collecting input through meetings was an essential and time-consuming practice. P1 said representatives of diverse interest groups frequently approached them to lobby the politicians. He did not see this as a problem. On the contrary, P1 exclaimed, "I love lobbyists! They are extremely useful, very rarely they come with tricks, very seldom they are bought and have sleek suits and such. Most of them are experts themselves from some interest group, and they are completely open about their interests". A vital quality of the lobbyists, according to P1, was that they knew that politicians needed solutions. P4 also appreciated how affected actors were open about their opinions and standpoints.

Similarly, P3 pointed to the impact of concrete case studies regularly provided by companies or associations. Often, they offered numeric information about the economic consequences of policy proposals. P3 mentioned as an example an ongoing discussion about a change in the CO_2 tax regime. In this case, he and others had received calculations that showed how the proposed change might make replacing oil with natural gas much less attractive. He perceived this potential effect as a weakness. In general, P3 found statistical information particularly influential, more so than most of the other interviewed politicians and political advisors. For example, P4 emphasised that the effect of numerical information depended on the issue. "It's very case dependent!"

P3 described the political advisors as an essential source of knowledge: "My acquisition of knowledge is intricately linked to their knowledge and their contacts. They [the political advisors] are employed because they are professionally solid in one area". However, he also emphasised that ENGOs, industrial associations, and companies regularly offered him information. This situation made him "become a recipient or the one who does not access [information] but the one who is accessed". The Standing Committee occasionally went on field trips to meet with industry or research communities to be informed and get a more hands-on feeling of the situation. P3 and all the other politicians described such field trips and meetings with relevant actors and organisations as providing essential input.

Thus, the politicians and political advisors' domestication of both quantitative and qualitative information was based on rhizomic learning, a non-linear, non-hierarchical engagement (Unander and Sørensen, 2020). They used a wide range of sources without clearly ranking them in terms of relevance or reliability. The rhizomic learning was a defining feature of the Pragmatic management of information. This approach owed to the nature of their tasks. Bluntly stated; they needed information to make policy. The politicians gathered information by combining sources, and they described helpful information in generic terms, such as short, relevant, and correct.

This practice reflected the time pressure to which the politicians often referred. For example, P3 mentioned previous White papers and the state budget as valuable sources of information. However, when asked if he had time to read such documents, he quickly responded, "No, no, no, very, very, very little. It's like surplus work if I get restless on the weekends".

To sum up, the Pragmatic management of information narrative describes the domestication of information as shaped by assessing its usefulness in a given context of political concerns and available alternative sources of knowledge. The quantification of the climate and energy policy area was appreciated, but all the interviewees articulating Narrative 3 also emphasised the need to acquire qualitative information. The ensuing sensemaking would result in use or non-use of the

information in policymaking. Cognitive domestication was characterised by rhizomic learning, which is consonant with the pragmatism they conveyed.

Conclusion: Cautious domestication of numbers in an audit-oriented policy culture

As we saw in the introduction, many scholars are concerned about the growing impact of numeric information in policymaking. Porter (1995) formulates this belief succinctly when he argues that trust in people has been replaced by trust in numbers. From this point of view, we would expect that the comprehensive quantification of climate and energy issues evident from White papers and other government documents would steer policymaking. The domestication of information should reflect a strong confidence in the provided numbers. Our study provides a more nuanced and complex picture.

The three narratives, Numerical engagement, Uncertainty, and Pragmatic management of information, describe a fascinating and complex ecology of numeric information in climate and energy policymaking. The interviewees explained the Standing Committee of Energy and the Environment as the centrepiece of the ecology since this committee would assemble, synthesise, and assess the flows of information supplied by the efforts of the ministries and the directorates. In addition, the interviewed politicians also acquired information from other actors and sources. Thus, when we look at the accounts of how information flowed, the ecology appears quite open and penetrable as it feeds pragmatically on diverse categories of input from a comprehensive range of sources. The pragmatic assessments and choices made by the politicians reflected their purpose: climate and energy policymaking.

Buck (2021, 55) criticises "the contemporary obsession with metrification, accounting, and modelling" in the climate field, which she claims may lead to misguided policymaking. None of our interviewees even hinted at such problems. In all three narratives, the quantification and metrification of climate and energy issues appeared pervasive but also accepted as a matter of fact without explicit criticism. This lack of critique fits the observation that the interviewees' accounts did not reflect any tyranny of metrics in the sense of Muller (2018) and no articulated experience of pressure to base policymaking strictly on numbers. Instead, they related a cautious domestication of numeric information, where qualitative input was sometimes more important. Even the interviewees who worked with calculations, articulating Narrative 1, Numeric engagement, emphasised that qualitative knowledge could be required, for example, when explaining behaviour or the effects of policies on companies' decision-making.

The interviewees described their domestication of the provided numeric information in ways that reflected trust. However, this trust came with modifications. Narrative 2, Uncertainty, expressed the qualifications most clearly as the need to be concerned with errors of measurements and the assumptions and the simplifications underlying model calculations. The interviewees emphasised the uncertainties of performance measurements and the incidental emergence of many numeric targets. Moreover, some interviewees expressed worries that politicians and the public did not take the uncertainties sufficiently seriously. Several complained that there was too much trust in numbers, and they said that they made considerable efforts to emphasise the contingencies of the policy-related numbers that they shared with politicians.

Moreover, both Narratives 1 and 2 showed that trust in numbers was related to trust in people and institutions. These interviewees were not indifferent to the origin of the numeric information, and trust had to be achieved. Thus, we do not see unreflexive assumptions about mechanical objectivity (Porter, 1995) in the information ecology of climate and energy policymaking.

The issue of trust was also present in Narrative 3, Pragmatic management of information, but without modifications related to uncertainties and errors of measurement. The politicians and political advisors accepted the numeric information the ministries and directorates provided. However, they said they put equal trust in actors from industry and interest organisations such as ENGOs. These interviewees explained that they assessed information based on its relevance

to their policymaking. The pragmatism of their domestication implied a right to balance the diverse categories of information while claiming to be concerned with appreciating "the larger picture", including party politics. The outcome depended on the issues at hand. Numeric information could be considered essential and decisive, for example, when engaging with the number of accidents in offshore oil and gas explorations, but not in discussions about opening new oil fields. In the latter case, value-based arguments had a greater impact.

The application of domestication theory proved helpful in developing the three narratives, as it asks for a focus that combines an emphasis on practice, sensemaking, and learning. A primary assumption is that actors have the agency to engage in a contingent manner with artefacts or knowledge, in our case, numeric information. This belief fitted our observation of the varied practices of working with numeric information, from reviewing and calculating targets and policy measures to assessing uncertainties in the available knowledge to deciding policies based on pragmatic management of many sources of information. Narrative 1 emphasised the existence of an audit culture where most targets were formulated numerically, and their attainment was evaluated based on metrification, resulting in indicators and measurement. However, this audit culture was not articulated in the two other narratives and was not mentioned by all the interviewees who offered Narrative 1.

Further, the sensemaking of quantitative information was also diverse. Narratives 1 and 2 highlighted positive aspects of quantification while acknowledging uncertainties and the need to include qualitative information. However, some interviewees emphasised uncertainties and possible errors of measurement. A few displayed an affective relation with numbers, while others considered quantification trivial. In Narrative 3, sensemaking was more ambiguous. The politicians appreciated the widespread quantification of climate and energy issues as valuable but in a contingent manner that often rendered the effects of numbers opaque. For example, we saw that policy recommendations tended to be articulated without using numbers. Overall, the sensemaking accounts in Narrative 3 displayed caution. None of these interviewees related to numeric information as singularly authoritative or in an unequivocally enthusiastic manner. However, on the other hand, nobody dismissed such information as untrustworthy or problematic.

We linked learning, the cognitive aspect of domestication, to information gathering since the interviews did not bring forward other forms of learning. We heard only a few complaints that numbers were difficult to understand. A striking feature of all three narratives was the many sources that could be used. Narrative 3 described the most intriguing and complex gathering process, which we described as rhizomic learning (Unander and Sørensen, 2020). This process was characterised by a lack of ranking of the sources and pragmatic use of information. The transfer of numeric information from the government administration to politicians, supposedly their dominant source of such information, was not linear but involved interpretation, negotiation, juxtaposition of numbers from other sources, and the inclusion of qualitative input that could be decisive (see, e.g., Næsje, 2002 for an illuminating case where moral arguments led to a disregard of numeric information in the Parliaments' decision-making).

As mentioned, we chose domestication theory to guide our analysis because it allows a critical assessment of the frequently assumed performativity of numbers by emphasising the agency of users (in our case, policymakers) and focusing on the details of policymaking. Our findings demonstrate that the performativity is limited. Thus, we should not overestimate the discursive strength of numbers as input to climate and energy policymaking. This claim is supported by observations of scientists and other experts saying that they need to engage in numeric work to persuade policymakers to engage with the quantitative information they supply. Numeric work means explaining the basis and relevance of such information (Jørgensen and Sørensen, 2023). Definitively, the interviewees considered quantification essential, but their engagement with numbers was more reflexive than suggested in much previous research. The predominant strategy of domestication of numeric information was careful and

pensive, acknowledging the diversity and possible inconsistency of sources and the potential importance of qualitative input. Thus, policymaking concerning climate and energy issues in Norway is guided but not always decided by numbers.

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How Sociotechnical Systems Adapt to Change: Reproductive Imaginaries in the Co-production of Assisted Reproductive Technologies

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Abstract

This paper addresses the topic of the dynamics of sociotechnical change of reproductive technologies and, in particular, the relationship between sociotechnical systems as described by TP Hughes and their environments. The co-production approach and sociotechnical imaginaries defined by S Jasanoff and SH Kim allow to explain the dynamics of technical change through the interweaving of technoscientific and social practices; and the concept of 'reproductive imaginaries' provides a better analysis of the back and forth adjustment between the system and its environment in a way that avoids the soft determinism that still persists in traditional accounts of sociotechnical change. I argue that reproductive technologies are co-produced with its environment in dialectical processes through specific technologies and reproductive imaginaries. Finally, I defend that this system performed adaptations even when it is mature.

Keywords: Sociotechnical Imaginaries, Large Technological Systems, Assisted Reproduction, Reproductive Imaginaries, Philosophy of Technology

Introduction

It is becoming increasingly difficult to ignore the growing of reproductive technologies in our Western societies. Reproductive technologies are often seen as disruptive technologies (e.g., Cohen et al., 2017) that are transforming some of our most fundamental concepts, such as motherhood, family, and kinship. However, the lack of a global perspective on the structure and dynamics of this complex sociotechnical system makes a challenge to estimate the scope of such changes.

The interactions of technological developments and society have been object of intensive study, mainly in Science and Technology Studies (STS) research field. In recent years, the understanding of the co-production of epistemic, technological, and social orders has gained relevance, that is to say, the way they jointly come into being (e.g., Felt et al., 2017: 9). Within this interdisciplinary field, the theory of Large Technological Systems (LTS) (Hughes, 1983, 1987, 1994) offers an account of the structure and dynamics of such systems that enables a holistic understanding of LTS, such as assisted reproductive technologies (ART).[1] From a historical perspective, Hughes explains the dynamics of technology and society through different phases in the development and

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evolution of technological systems according to the predominant activity: "invention, development, innovation, transfer, and growth, competition, and consolidation" (Hughes, 2012: 50). These phases may overlap and do not always follow the same order. According to Hughes, technologies are more permeable to the influence of environment when they are young, while, as they consolidate and acquire style and momentum, they tend to adopt certain paths. This makes them less receptive to environmental influences and tends to shape them (Hughes, 1994).

Also, as technology historian Richard Hirsh argues, the value of LTS lies in "emphasiz[ing] that the motivators of technological change extend beyond the technical realm and have origins in the social world" (Hirsh, 2016 cited in Sovacool and Hess, 2017: 716). However, later developments in the LTS theory have focused on the structure, postulating new phases (i.e., Sovacool, et al., 2018) or adopting a multilevel perspective (i.e., Geels, 2007), and dispensing with cultural meanings and narratives regarding the technologies and goals for the society in which they are inserted. For some critics, they focus too much on the structure of the systems and neglect the agency of the users (Shove and Walker 2010; Rutherford and Coutard, 2014) or the power relations within the system (Smith et al., 2010). So, still there is no clear explanation of how the system and the environment are related nor the reasons why agents act. To the contrary, within STS studies, the co-production approach (Jasanoff, 2004) and the development of the concept of 'sociotechnical imaginaries' (STIs) (Jasanoff and Kim, 2015) provide more adequate tools to explain the dynamics of technical change through the interweaving of technoscientific and social practices.

In this essay, I analyse reproductive technologies as a sociotechnical system (Hughes, 1983) because it provides a better understanding of the evolution and dynamics of these technologies. I also use a co-production approach and STIs since they allow presenting a more detailed explanation of agents' reasons for action and their relationship with the system. In particular, I use the term 'reproductive imaginaries' to refer to the collective visions of the future related to reproduction that emerge and evolve with the sociotechnical system of ART.

Reproductive imaginaries are a type of STI and, therefore, it is important to point out that they are not merely collective visions about motherhood, infertility or kinship that are institutionally articulated in different cultures (see Table 1). Reproductive imaginaries are reflected in the

Table 1. Some types of reproductive imaginaries identified and their elements.

	Types of reproductive imaginaries				
Elements of reproductive imaginaries		System builders and ART system	Christian Groups	Socialist embriologist	Lesbian Couples
	Importance attributed to the family in the life project	Heterosexual nuclear family model			Homosexual nuclear family model
	Importance attributed to motherhood in the life project	Naturalisation of motherhood and reproduction			Social motherhood
	Infertility vision	Infertility as a disruption or problem: social pressure to reproduce			Problem in social terms. Partner does not have the necessary gametes
	Vision of ART	Technological fix	Unnatural; it threatens the life of cryopreserved embryos	Therapeutic	Technological fix
	The importance attributed to genetics in shaping kinship ties	Genetic kinship			Kinship based on social ties and legal arrangements

design of specific technologies and comply with certain techno-scientific projects (Jasanoff and Kim, 2009), whether articulated and promoted by nations or by organised groups such as corporations (e.g., Valencia Infertility Institute, IVI), social movements (e.g., feminism) and professional societies (e.g., European Society of Human Reproduction and Embryology, ESHRE) (Jasanoff and Kim, 2015). Moreover, reproductive imaginaries are plural since different visions can co-exist in tension (Jasanoff and Kim, 2015) in the same society, such as, for example, the degree of importance attributed to genetics. In addition, they are in a dialectical relation with technoscience and society (Jasanoff and Kim, 2015), so they are dynamic and can vary as the groups that support them change. For example, lesbian couples were able to access assisted reproduction and develop shared maternal projects in Spain thanks to certain legislative changes that other surrounding countries like Italy or Switzerland do not share. STIs codify both visions of what is attainable through technoscience and desirable ways of life. Continuing with the previous example, these imaginaries are committed to the diversity of family models achievable through assisted reproduction and, therefore, they should be understood in normative terms.

Reproductive imaginaries project certain forms of desirable reproductive futures and, in this sense, the axes of power such as gender, race and social class are involved in the imaginaries to the extent that they articulate the materiality of the subjects (collectives) that they maintain, the desires these agents project, and their sociotechnical practices. That is why the analysis must focus on the collectives committed to the "renewability of valued forms of life", the institutions in which these desires are expressed and the practices that allow them to develop those visions (Jasanoff and Simmet, 2021:5).[2]

My aim in this paper is to offer a better understanding of the dynamics of sociotechnical change in reproductive technologies and, in particular, the relationships between the ART system and its environment. My hypothesis is that ART perform adaptations to their environment in order to maintain itself, even when it is mature. These adaptations are the result of tensions between reproductive imaginaries-related forces within the system and in its environment.

To explain the tensions and dynamics of technological change, I use the forces of classical mechanics as an explanatory metaphor. Centripetal forces are real forces causally associated with the action of some agent outside the body on which they act. On the other hand, centrifugal

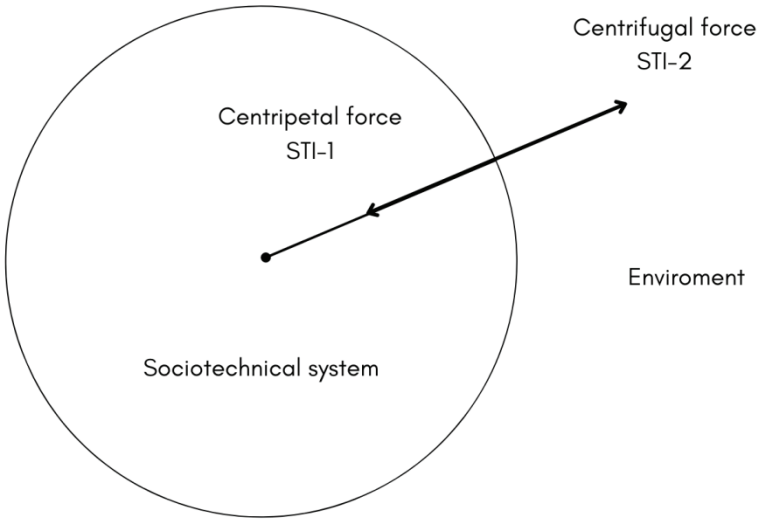

Figure 1. Representation diagram of the metaphor of the forces where the LTS and STI approaches are related. STI-1 corresponds to the imaginary of the system. STI-2 is a dissident imaginary (e.g., lesbian couples). Co-production is the continuous result of their struggle.

force is the tendency of an object to resist any change in its state of rest or motion (Newton, 1999). In my view, the STI of the system acts as a centripetal force that tries to capture the elements of its technological environment. In contrast, the dissonant STI of the environmental agents maintain pressure in the opposite direction (see Figure 1). As Hughes points out, when a system is young, it is permeable to its environment, while as it gains momentum it tends to exert determinism over its environment in an attempt to control it (1994). Dissonant STIs act as centrifugal forces pushing the system to open up by making adaptations in order to extend its dominance and maintain itself. This combination of approaches results in a methodology that focuses on explaining the reasons that guide the agents involved in technological change, without losing sight of the evolution of the technological system. The metaphor of forces anchors both perspectives and functions as an interpretative tool for the co-production process of the technological system and its environment.

Methodologically, this paper follows the phases identified by Hughes in the development of technological systems. The main features of these phases were used as criteria for analysing the phenomenon. Narratives and episodes were selected to illustrate the agents' reasons for acting and how reproductive imaginaries are constructed. The main features already described were also taken into account. For instance, during the invention phase, *A Matter of Life* (1980), the memoirs of Robert Edwards and Patrick Steptoe, proved to be an essential source for comprehending how their worldview translates into their decisions and how it impacts the IVF design. In subsequent phases, I selected scientific literature from major journals in the field of reproductive medicine and biology, such as *Fertility and Sterility*, as well as interviews with relevant scientists in the media and the community's own IVF histories as primary sources. This allowed me to explore reproductive narratives and imaginaries. To provide context and a comprehensive overview, I also consulted Martin Johnson (2011, 2019) and Kay Elder's (Johnson and Elder, 2015) works on the history of IVF[3] and Sarah Franklin's research on the interconnections between ART, the global economy, and transnational politics (Franklin et al., 2000; see also Salter 2022). Additionally, I used case studies such as gamete donation (e.g., Lafuente, 2017) and the use of ART by lesbian couples (e.g., Mamo, 2007) to outline scenarios of conflict and negotiation.[4]

Moving forward, in the following section, I introduce the concept of reproductive imaginaries in the context of the invention of *in vitro* fertilization (IVF). Then, I carry out a co-productive analysis of ART as a LTS through the phases postulated by Hughes after which I offer an explanation of the system's adaptations through different examples. Finally, I present my conclusions.

Reproductive imaginaries in the invention of IVF

To understand the scope and participation of reproductive imaginaries in co-production with ART, I think it is worth pointing out some constitutive elements already found in the origin and invention of IVF. During the 1960s and 1970s, a period in which research was carried out leading to the birth of the first baby in the world to be born through IVF, most gynecology and obstetrics professionals understood motherhood as a natural phenomenon desired by all "normal women" (Stanworth, 1987: 15). Those who rejected the 'maternal instinct' were considered selfish, deviant, or deficient as women (Badinter, 1980). In this period, the naturalization of motherhood was a solidly established representation in society. This way of understanding motherhood was inherited from the 18th century ideals of motherhood (Knibiehler, 2001: 53) and exerted strong ideological pressure on women to be mothers according to defined parameters within the framework of the nuclear family. A biological essentialism slips into this imaginary according to which the feminine is related to the maternal. This identification was strongly criticised by many feminist authors (i.e., Beauvoir, 1949; Badinter, 1980) who argued that there is no feminine essence, but rather cultural representations about what it means to be a woman (Tubert, 1996).

At the same time, the rise of neo-Malthusianism in the Anglo-Saxon world during the first decades of the 20th century gave rise to movements

for contraception and family planning. At the beginning of the 1960s, there was a remarkable increase in the birth rate in general, known as the *baby boom*, which also led women to be interested in contraception (Knibiehler, 2001: 88-89). With the popularization of the contraceptive pill and the intrauterine device (IUD), women began to take control over their fertility. As the historian Yvonne Knibiehler points out, "the biological function became the result of a decision: it was no longer a matter of passive reproduction, but of human procreation in which reason and affectivity intervened" in such a way that "when the desired child comes into the world, the joy must be total" (Knibiehler, 2001: 97-98).[5] It was an ambivalent and changing context in which traditional ideas of family and motherhood coexisted with social and technological changes (i.e., contraceptive pill, IUD), which also involved transformations in family and couple models.

In the 1960s and 70s, the main concern within the scientific community and gynecological field was overpopulation and family planning, while infertility was considered an irrelevant issue. Infertility only affected a minority of the population and was therefore not a major clinical problem due to concerns about population growth (Johnson, 2011: 258). However, those who would become known as the scientific parents of the world's first IVF baby, physiologist Robert G. Edwards and gynecologist Patrick Steptoe, differed from this dominant view (Johnson, 2011).

Steptoe was a family man and grew up in a happy family of eight brothers and sisters (Edwards and Steptoe, 1980: 11). He empathised with the women with reproductive problems who came to his office in the 1950s and 60s. The feeling of guilt that those infertile patients felt at not being able to become mothers and have their "own" family had a great impact on him during his medical school days. He felt a "rush of sympathy for them" (Edwards and Steptoe, 1980: 12) and that feeling accompanied him throughout his professional career. This empathy with infertile women and their husbands was also shared by biologist Robert Edwards, who came to strongly believe in the right of such couples to have their own offspring (i.e., Edwards and Steptoe, 1980: 101-102). Edwards, father to five girls with geneticist Ruth Fowler, repeatedly expressed a feeling of solidarity with the suffering of childless couples (i.e., Edwards and Steptoe, 1980: 40).

This empathy occurs within the framework of a shared worldview in which the family occupies a preponderant place. The common idea of family in this reproductive imaginary is made up of a heterosexual marriage union and its progeny. It is important to point out that, in this worldview, the family is incomplete in the absence of offspring, causing suffering. In addition, another very relevant idea reflected in the design of IVF is the generation of kinship ties based on the genetic relationships between family members.

Genetics was central to Edwards's thinking despite being rudimentary and alien to most reproductive biologists during the 1950s and 60s. As a physiologist, Edwards had trained alongside geneticist and reproductive biologist Alan Beatty, who influenced his interests and values (Johnson, 2011). The biological tie between parents and progeny was especially relevant. Edwards himself recalls how his "primary preoccupation was what it had always been- to study human embryology and allow women, who were seemingly forever condemned to a life of infertility, to bear their own children fathered by their own husbands" (Edwards and Steptoe, 1980: 86). Thus, it was not just about helping infertile couples become parents. The objective was to reproduce a specific family model and establish kinship relationships based on the genetic tie between both parents and their offspring.

The genetic tie between parents and offspring acquires special value in the Euro-American context where kinship relationships are understood in biogenetic terms. From this perspective, reproduction is seen as a fact of nature, omitting marriage as a social agreement and its role in the construction of kinship links (Strathern, 1992). The reiteration of this imaginary about how human relationships are built is a cultural practice (Strathern, 1992: 17) that has the effect of naturalizing the family. Thus, the nuclear family is seen in the Euro-American context as a natural phenomenon and "biological facts" acquire a prominent position, a relevant social meaning (Donoso, 2012: 44-45; Strathern, 1992: 19).

In this context, infertility is viewed as a disruption to the normal progression of life and an obstacle to the creation of the family which generates dissatisfaction, misery and suffering (Franklin, 2002). As the sociologist Sarah Franklin has pointed out, added to the social pressure to reproduce that infertile people experience is the idea that there is a kind of natural or biological impulse to have children that cannot be ignored. In the author's words: "It is represented as being genetically determined by our evolutionary heritage and essential to our survival both as individuals and as a species" (Franklin, 2002: 91).

This kind of 'reproductive instinct' or need to have biologically related children in order to transmit 'genetic inheritance' is a discourse that frequently appears in the field of assisted reproduction. Patrick Steptoe himself believed that "[i]t is a fact that there is a biological drive to reproduce" (cited in Stanworth, 1987: 15). Robert Edwards and his collaborator, David Sharpe, also shared this vision when considering that "the desire to have children must be among the most basic of human instincts, and denying it can lead to considerable psychological and social difficulties" (Edwards and Sharpe, 1971: 87). From this supposed biological impulse follows the idea that the formation of the family within the framework of heterosexual marriage is not so much a social convention as a natural progression of life itself (Franklin, 2002: 92) and, therefore, "the right of some couples to have children" (Edwards and Sharpe, 1971: 87) cannot be denied. Consequently, technoscience appears as the savior or helper for infertile couples and guarantor of that right. IVF is transformed into a technological arrangement that mimics nature.

The co-production of an LTS: from IVF to ART

Since the beginnings of IVF in mice in the 1960s, this technology has grown from an experimental technique to a complex technological system. The innovations and growth of IVF have made it easier for this technology to be placed at the center of an entire sociotechnical system in which other technologies orbit. The term assisted reproductive technologies (ART) is commonly used and I use it to refer to the large socio-technical system built from IVF.

Invention

The invention phase is relevant to understanding how certain ideas become part of the technologies we have. In LTS terms, the physiologist Robert Edwards and the gynecologist Patrick Steptoe could be understood as inventor-entrepreneurs or system builders. Most likely, Jean Purdy, co-developer of IVF, would not have been considered in these terms by Hughes, not only because she does not contribute to the story of great enterprising men, but also because her work as a laboratory technician could easily be classified as routine and lacking in creativity. Nevertheless, co-production allows shifting from inspired individuals or small groups to communities insofar as it maintains that, although imaginaries are collective, they can arise from individuals or small groups (Jasanoff and Kim, 2015). For this reason, although I will begin by giving greater relevance to the problems expressed by the system builders, I want to make it clear that the road to IVF has been a long one of research in reproductive physiology, technical developments in the preparation of laboratory samples as well as in obstetric and gynecological surgery and required the collaboration of other gynecologists (who supplied eggs for research), nurses, laboratory technicians and, of course, infertile women who desperately wanted to become mothers.

I shall start with a passage from Edwards and Steptoe's memoir *A Matter of Life* (1980), as it illustrates the extent to which both designers' beliefs about end-users and their reproductive imaginaries influenced the co-production of this technology. The team led by Edwards, Steptoe and Purdy at the hospital in the British town of Kershaw had been administering hormones for some time as part of the protocol to induce ovulation and obtain a greater number of mature eggs (and, ultimately, increasing the chances of achieving a pregnancy). After several failings, they concluded that these hormones had shortened the patients' menstrual cycle. Thus, in the course of egg collection, their fertilization, and the development of the embryos, the patient's body was preparing to menstruate. This made it really unfeasible for

them to be able to retain the embryos. However, without the hormones, they could only get one egg per cycle. Consequently, the team had to monitor each patient individually to retrieve the egg at the optimal point of maturation. Faced with this reverse salient, Edwards and Steptoe deliberated over the possibility of exchanging their patients' ovules in order to facilitate the uterine implantation of the embryo.

> "Of course we could have taken an egg from, say, Mrs A who had been given the fertility drugs, fertilized it with the sperm of Mr B and then transferred the resultant blastocyst into the womb of Mrs B who would not have received fertility drugs. Then without a doubt Mrs B would become pregnant – only the baby growing inside her would not have been her own, though her husband would have been the father.
> Patrick, seeing how much his patients longed to have babies, toyed with this idea of embryo transfer. […] Surely such a baby would be much loved by Mrs B?" (Edwards and Steptoe, 1980: 122).

After considering possible moral and legal problems, they decided to discard that idea. As Edwards briefly mentioned, it was too complicated and he was "against it" (Edwards and Steptoe, 1980: 122). Steptoe agreed with him.

This conversation between Edwards and Steptoe reflects how they were aware that a possible solution to the implantation problem they faced relied on egg donation (a common practice today). According to the account, Steptoe was more inclined than Edwards to offer this alternative to patients as a way of satisfying their desire to be mothers. They both agreed that a baby born this way would probably be loved. However, they were not certain. In addition, legal problems could arise, such as disputes over parental responsibility. Thus, they were faced with a series of complex circumstances in which both basically agreed that genetics played a preponderant role in establishing kinship relationships.

The manner in which Edwards and Steptoe addressed these critical issues and resolved this inconvenience marked the future course of *in vitro* fertilization. Rejecting egg donation meant opting for a less efficient path in technical terms. If they had chosen this route, they would have achieved a birth in one of their patients much sooner. However, the imaginary that guided their practices led them down a much more arduous path: from dropping hormone therapy to following the natural cycle.

The natural cycle strategy presented new difficulties and critical problems for the entire team at technical, organizational, and personal levels (Johnson, 2011). As Steptoe recalls, this new strategy involved changes in their practices: "It would no longer be possible to carry out operations when it suited me or my team" (Edwards and Steptoe, 1980: 146). To deal with these reverse salients, the team had to calculate the exact interval of time in which each patient's egg (only one) would be mature and aspiration could be performed by laparoscopy to then proceed with in vitro fertilization. If all went well, only one embryo would develop, although it might not reach the blastocyst stage (the optimal for transfer). If the embryo presented any problem during its development, it would have to be discarded and the procedure started again in the next cycle. However, even if the whole process had gone according to plan, the embryo could not be implanted and the pregnancy could not take place. It should not be forgotten that the patients were infertile. These were generally women having clogged Fallopian tubes due to infection, but there were also other causes, both known and unknown at the time, that could ruin all their efforts.

Ideas about family and kinship in the phase of invention and development played an important role in the expectations of end users. At this time, the end users were married heterosexual couples rather than individual patients. In the reproductive imaginary of the development of IVF, infertility and its technological fix were confined to the framework of the nuclear family. In the passage above, Edwards and Steptoe deliberated and moved forward without consulting their patients about possible drawbacks. From their parameters, their patients wanted their "own" children from their "own" husbands and therefore it was not enough to be able to offer them a child that was not genetically linked. This issue turned out to be crucial in redirecting their research practices. Thus, the final objective of IVF was configured: to

provide infertile couples with genetically linked offspring. At the same time, they clearly defined the profile of the possible users of this technology - infertile heterosexual couples for whom an opportunity had now opened up (Edwards and Steptoe, 1980: 185)-, thereby excluding other possible users, such as single women, something that changed as the sociotechnical system matured.

Finally, on July 25, 1978, Louise Joy Brown was born in Oldham. She was the first baby in the world to be born through IVF. Thirty-two years later, the success of this technological fix for infertility was distinguished with the 2010 Nobel Prize in Physiology or Medicine.

Development and Innovation

The road to the invention of IVF was long and winding. The British team resolved numerous challenges, both technical and social. However, in the 1970s there were other groups looking for techno-scientific remedies for couples suffering from infertility. The success of 1978 made it easier for many techno-scientific developments aimed at improving the effectiveness of *in vitro* to occur. These innovations mainly improved culture media and technical instruments for oocyte retrieval (needles, introduction of ultrasound in laparoscopy) and embryo transfer (cannulas), and adjusted hormone doses (Leeton, 2004).

A short time later, another technology, already anticipated by Edwards, was to prove an important turning point. The first use of deep-frozen semen was reported in 1983, and the first birth from a frozen embryo occurred in Monash, Australia, in 1984 (Mahadevan et al., 1983; Downing et al., 1985 cited in Leeton, 2004). Cryopreservation improved the efficacy of IVF because it favored the collection of a greater number of ovules and, therefore, the development of more embryos, increasing the chances of success and allowing the excess to be stored for other attempts. This surplus also led to the donation to other women and the development of gamete banks.

In this context, new inconsistencies began to emerge, not only in the form of ethical problems, such as what to do with surplus embryos and whether they have the right to life, but also religious ones. In 1983, Gamete intrafallopian transfer (GIFT) was offered in Ohio (USA) for the first time as an alternative, as it was considered *more ethical* by Christian groups. Christos Mastroyannis explains in *Fertility and Sterility* that "[o]bjections by the Roman Catholic Church to these techniques arise from an understanding of the procreative act as 'a physically embodied love act', a consequence of the heterosexual nature of the human race" (Mastroyannis, 1993: 389). In this procedure, the gametes were placed directly into one of the Fallopian tubes. They thought that in this way fertilization occurred in a more natural way.

These technologies competed with IVF, driven mainly by the strong influence of religion in the reproductive imaginary. Although the success rates using GIFT and its derivatives were initially higher than by using *in vitro* fertilization, improvements in the procedures made it easier for the latter to gain ground. As Lauren Bishop and her team explain, "given the minimally invasive approach of IVF, 78% of practitioners preferred this method over tubal transfer of gametes or zygotes" (Bishop et al., 2018: 206). These other technologies required the use of laparoscopy, which made them more invasive than *in vitro*, which already used the vaginal route. In addition, they carried risks, such as ectopic pregnancy and those typically related to the use of general anesthesia.

In the years following IVF, this technique coexisted and competed with other technologies with which it shared both objectives and users. In these other technologies, end users were assumed to also be (heterosexual) married couples (i.e., Mastroyannis, 1993: 390). Conflicting values also arose, demonstrating the dynamics of reproductive imaginaries; for example, the conflict between the value of genetic inheritance versus the value of the life of the excess embryo which could be adopted.

Other technologies also emerged around *in vitro* that led to the development of the technological system. The first micromanipulation techniques developed in the 1980s were partial zonal dissection and sub-zonal insemination, aimed at "enhanc[ing] the success of IVF in couples with male factor infertility" (Bishop et al., 2018: 207). Both can be considered important precedents for intracytoplasmic sperm injection (ICSI).[6] In 1992,

the success of ICSI with the birth of four babies was reported in Brussels, Belgium (Palermo et al., 1992 cited in Bishop et al., 2018). The use of ICSI doubled the fertilization rates as compared to previous ones (Bishop et al., 2018: 207). ICSI is considered almost as important as *in vitro* fertilization because it allowed to start "treating" the male factor of infertility (Palermo et al., 2018: 196). Like IVF, its purpose is not to cure through medical treatment, but to facilitate the creation of genetically based parent-child bonds through a technological fix.

By injecting round spermatids into oocytes (ROSI), two babies were born in 1994 in Paris, France (Tesarik et al., 1995). ROSI technology and its subsequent developments allowed men without sperm to become genetically linked fathers, something completely unthinkable until then.[7] These technologies sought to dispense with sperm donation, which was considered a less desirable alternative. The goal of these technological developments was to generate genetically linked blastocysts and, ultimately, babies. In this way, IVF is growing as a system, accommodating new technologies within its system and directing innovation towards its objective.

Transfer, Growth, and Competition

In IVF accounts, some groups generally stand out over others and this also shows the collaborative networks and rivalries of the early years. Births in the UK (1978), Australia (1980), the USA (1981) and, to a lesser extent, Sweden and France (1982) are frequently included in the accounts (i.e., Leeton, 2004; Brown and Steirteghem, 2018). However, the second IVF birth in the world was in India, two months after the birth of Louise Brown. In his protocol, physiologist Subhash Mukherjee included the use of hormones, the cryopreservation of the ovules (two obstacles for the British team) and the vagina as a means of access in oocyte retrieval. Another frequent omission is that of the first baby born in the Czechoslovak Socialist Republic in 1982 through the efforts of gynecologist and researcher Jan Tesarik and his team. It is not clear if this oversight is due to the fact that it was presented as an alternative to the protocol used in England. This procedure was performed while also doing reconstructive surgery on the uterine tubes, so it had a therapeutic purpose (Tesarik et al., 1983). In contrast to the British procedure, Tesarik did not wait for the embryo to develop. Another possible reason for it being overlooked might be the hostile politics and rivalry between capitalist and socialist countries during the Cold War.

The different protocols followed by both Mukherjee and Tesarik are an example of the reproductive imaginaries interweaving in their decisions and the final configuration of their technological developments. The paths to IVF were different, as was their reception in Europe and India. Also, there are differences between the contexts in which these teams had worked, the social and scientific perception of their work, and the tragic outcome of Dr. Mukherjee on both a professional and personal level (Ferber et. al., 2020). Although further investigation would be necessary, this example is indicative of the plurality of reproductive imaginaries as well as their situated and contextual character.

Groups excluded from the main narratives aside, collaborative networks developed alongside rivalries. Jean Cohen, a French biologist on the team from the town of Sevres, recalls how isolated groups were in different parts of the world, working in environments that were hostile and indifferent to their work (Cohen et al., 2005: 440). Anna Veiga, a Spanish biologist and the scientific mother to Victoria Ana (the first IVF girl to be born in Spain in 1984), explained in an interview that "[it] was not an impression, it was evident. There was tremendous competition between two groups, ours and the one led by Dr. Marina, also in Barcelona. We knew perfectly well that they were doing the same thing as we were. Frankly, it was a race" (Elcacho, 2012: 8).[8] Veiga also recalls the added difficulties of those years when there were still no specific training courses in higher education institutions (Elcacho, 2012).

Despite the rivalry, the groups shared channels of scientific communication, sometimes through scientific congresses, but mainly through scientific journals. The advances and difficulties of the different procedures tested, as well as the technologies and devices which drove them on were constantly reported in scientific journals such as the *American Journal of Obstetrics and Gyne-*

cology, Fertility and Sterility, *Lancet,* and, later, *Human Reproduction,* among others. In the 1970s, the American Society for Reproductive Medicine was one of the main focal points for research in the field and, by the end of the 1980s, the USA was a leading scientific power (Hobsbawn, 1995), attracting scientists from all over the world through its journals and conferences (Browm and Tarlatzis, 2005). In the 1980s the various groups began to develop scientific meetings of their own and created scientific societies (e.g., Browm and Tarlatzis, 2005). Thus, collaborative networks were formed which facilitated the transfer of techno-scientific results and the innovations that emerged around IVF.

Furthermore, a growth phase occurred and clinics proliferated in the USA, Australia and Europe (i.e., Leeton, 2004). In this period, new actors appeared on the political scene due to the ethical and legal problems that the development of these technologies aroused. Some of these issues were related to the legal status of children born through IVF and to the ownership and use of surplus embryos, as well as to the licensing and regulation of the practices carried out with embryos by assisted reproduction clinics and experimentation laboratories (i.e., Melo-Martín, 1998). The need to develop legislation to adapt to these new circumstances led many countries to convene expert committees to evaluate these new technologies.[9] One of the best known reports is the Warnock report in the United Kingdom (1984). This committee developed principles for the regulation of IVF and embryology that laid the foundations for subsequent legislation on the protection of embryos and their uses in research. In 1992 USA regulates the IVF industry, controlling the quality of the laboratories and forcing success rates to be communicated for consumer information. The guidelines and recommendations of scientific societies were insufficient and legislation was needed to protect the rights of infertile couples against misinformation and lack of transparency from the emerging industry. In 1999, ESHRE created the European IVF Monitoring (EIM) Consortium for data collection referring to legislation, public funding and registration systems on ART in different countries (Calhaz-Jorge et al., 2020).

Acquiring Style and Consolidation

During the 1980s, the use of reproductive technologies expanded rapidly, arousing misgivings in some social sectors as different as the feminist movement and the Catholic Church (Thompson, 2005). In the case of Spain, where the ART system has best matured, the volume of accredited centers has grown significantly compared to other surrounding countries (i.e., Alkorta, 2006). In the first decade since its introduction in 1984, the number of clinics grew to 190. After the economic crisis, in the short period of the past 5 years, the number of centers has not fallen below 300; in fact, over the past 3 years it has risen to 436 centers.[10] Since 2012, coinciding with the standardization of oocyte cryopreservation and the fact that the procedure was no longer labeled as experimental (Asensio and Palma, 2018: 81), these centers have not stopped growing. This is happening in a country where 80% of the centers accredited to offer IVF[11] belong to the private sector and where the Public Health Service's (PHS) portfolio of common services had excluded single women, lesbian couples and trans people from assisted reproduction until 2021 (Orden, 2021).

Spanish clinics, especially those in the Mediterranean arc, have become one of the main centers of attraction for so-called reproductive tourism (Lafuente, 2021; see also Vertommen et al., 2022). In this geographical area are found the pioneer IVF centers in Spain, such as the Institut Universitari Dexeus, the CEFER Reproduction Institute, the Bernabeu Institute and IVI. The latter merged with a leading American company in the sector in 2017, forming IVI-IRMA Global, a multinational represented in Europe, the United States and Latin America, after selling part of the company in the Middle East for 90 million euros (Muñoz, 2020). It has an average yearly turnover of 300 million euros and was recently bought for 3 billion euros (Casado, 2022).[12]

IVF has not only experienced significant changes at a quantitative level, achieving territorial and business transfer and growth at a global level, but it has also experienced qualitative changes, especially in the last two decades. The concept of 'platform technology' (Franklin, 2013) illustrates the nature of this technology as the foundation or support for various technological

deployments, without which they would not be possible, such as DGP, stem cell research and reprogenetics.

From the LTS perspective, I interpret these qualitative changes as the consolidation of the technological system and the acquisition of *momentum* (Hughes, 1987). IVF has become a complex and extensive technological system. This system is made up of other technologies (i.e., cryopreservation, PGD, artificial intelligence, etc.), artifacts (i.e., cannulas, Petri dishes, stretchers, etc.), scientific elements (i.e., books, conferences), organizations and institutions (i.e., courts, PHS administration), natural elements (i.e., gametes), and heterogeneous actors (i.e., infertile patients, fertile users, embryologists, gynecologists, psychologists, marketing teams, etc.), as well as connecting with other sociotechnical systems (i.e., PHS, the economic). Some of these systems and new technologies have come to constitute new fields using the embryos generated by IVF, such as stem cell therapies, thus moving away from the original function of the system (reproducing babies biogenetically linked to their parents).

The idea that the system has gained autonomy or "a life of its own" is indicative that it has matured and gained momentum (Hughes, 1987: 76). This autonomy is apparent. The sociotechnical system is sustained thanks to the social relations and institutions that participate in it (Jasanoff and Simmet, 2021). Some of these are the assisted reproduction units in PHS, private clinics (whether small or large companies), pharmaceutical companies, public and private research centers, governments and their legislation, scientific societies, associations of infertile patients, etc. In order for the system to behave in an inertial and apparently autonomous way, it is crucial that the interests of the system's social agents be focused around its function.

This explains why cryopreservation (of gametes, embryos, and ovarian and testicular tissue) and regeneration (of gametes and tissues) are two of the main lines of research and technological innovation. The cryopreservation of embryos and oocytes is an accepted and standardised procedure in clinical practice (Asensio and Palma, 2018) which facilitates the reproduction of genetically linked babies when people lack optimal gametes for spontaneous conception, either due to aging or being affected by various pathologies and/or treatments (e.g., cancer or endometriosis patients). Cryopreservation intervenes as a bridging and an accessory to *in vitro* fertilization. In contrast, regenerative medicine applied to assisted reproduction and its technological developments (i.e., platelet-rich plasma intra-ovarian infusion, ovarian tissue transplantation, artificial ovary and gametes) aim to restore reproductive function, and therefore ensure genetic linkage, although they are still experimental and need further evidence and evaluation (Sfakianoudis et al., 2020).

As I have argued so far, IVF is a technology that has grown to become a sociotechnical system whose function is to reproduce kinship relationships based on genetic linkage. In this sense, it has managed to articulate actors with heterogeneous interests, institutions and other technologies, becoming the center of ARTs.

System adaptations to the environment

A consolidated sociotechnical system like ART over time becomes increasingly impervious to the influences of its environment and acquires a tendency to configure it (Hughes, 1994). Matured systems tend to follow a particular path which is shaped by style. Thus, those kinds of systems also "tend to exert a soft determinism on other systems, groups, and individuals in society" (Hughes, 2012: 48) and "to incorporate the environment into the system, thereby eliminating sources of uncertainty" (Hughes, 2012: 47). However, following the case of ART, I have identified different adaptations to the environment. Thus, I try to explain the dynamic relationships between ART and its environment.

From my perspective, a system with style and momentum has a great centripetal force, that is, it has a great capacity to attract bodies towards the nucleus. IVF, whose function is to reproduce the links of genetic kinship, is at core of ART and other technologies within the system are adaptations that serve this function and its reproductive imaginary. The following example illustrates this. A heterosexual couple goes to a clinic claiming to have problems conceiving spontaneously. The

system operators, gynecologists and embryologists diagnose the woman with ovarian aging due to advanced maternal age and offer to replace her egg with a donated one.

Egg donation (or rather, the use of donor eggs) is one of the practices that has most contributed to raising the success rate of IVF (Lafuente, 2021) and is also one of the most used technologies in recent years in Spain.[13] The use of donor eggs in IVF means giving up the genetic tie of one of the parties, in this case, the woman.[14] As other authors have pointed out, these ovules "guarantee that the heterosexual couple conceives while maintaining the male genetic line" (Lafuente, 2021: 121).[15] In this way, the genetic link of the male, who is the undisputed father of the future child, is ensured and the system's reproductive imaginary is accomplished, while the identity of the mother is uncertain and must be reconstructed discursively.

Donated eggs become a technological solution to a problem of nature and the value of genetics is replaced by epigenetics and the gestation process (i.e., environmental factors and lifestyle can alter the expression of genes, thus, the baby's physical characteristics and health). In this context, the role of epigenetics as an enabler of the transfer of a kind of unique "substance" to the baby during gestation takes on fundamental relevance insofar as it facilitates the creation of kinship ties. Epigenetics is valued and occupies a relevant place within the system's imaginary as a substitute for genetics. According to Jenny Payne, the emergence of epigenetics in new conceptions of kinship may represent a paradigm shift to the extent that it redefines biological kinship (Payne, 2016: 494). Likewise, as Sarah Richardson (2021) points out, biomedical research in this field has proliferated in the last three decades, even though there is no clear consensus on the factors to consider or their correlations. From a critical review of the theories on the 'maternal imprint', Richardson's work shows the role of surveillance and control that these imaginaries exercise on mothers during pregnancy. Thus, through epigenetics, the ART system's imaginary restores the identity of the woman as a future mother and the role of the donor is overshadowed or estranged from the process by the product: the egg.

This technology reinscribes kinship ties in epigenetic terms for the woman within the heterosexual couple. This supposes an adaptation of the system in the face of a new reverse salient: the problematic ovum of the progenitor.[16] The system is adapted through the use of an IVF accessory technology which facilitates the reproduction of the IVF nuclear family model from 1978. The infertility taboo, still very much present in many reproductive imaginaries, operates in this context by contributing to the concealment of the donation if the couple so wishes (Fernández-Jimeno, 2022). Egg donation is one of the system adjustments to reproduce the same model of kinship.

In the above case, the reproductive imaginaries (and goals) of the clinic and the couple were the same. But, what happens when the imaginaries of a group of possible users differ from the system's imaginary? When the imaginaries of the environment and the system differ, a confrontation occurs, i.e., a fight between opposing forces. This conflict is resolved through negotiation or abandonment. An example of this is seen in the case of lesbian couples as users of ART.

In Spain, since the approval of the same-sex marriage law in 2006 and the change in social values, more and more lesbian couples are deciding to undertake social family projects (Imaz, 2014; Royo et al., 2020). This change in the environment placed the ART system face-to-face with a reverse salient: a new type of potential users appeared for whom the system was not prepared. One of the most common ways for these couples to undertake this project is through the use of artificial insemination by donor (AID) because it is a "safe and easy" way to carry out this project of joint motherhood. Lesbian couples think they can use these technologies to be mothers, but their project is conceived more in social rather than biological terms. Thus, the reproductive imaginary of lesbian couples differs from the reproductive imaginary of ART.

For gay and lesbian couples, the genetic link with their upbringing has not been so since they really lacked the means (Fernández-Jimeno, 2019). However, the introduction of the reception of oocytes from the couple (ROPA method) in private clinics' catalogs increases their options as consumers. This technology links genetically

to the woman who provides the egg and epigenetically to the woman who experiences the pregnancy. In this way, a discourse of "shared motherhood" is constructed in which the two women are mothers insofar as they share their "substance" with their child (Bestard, 1998 cited in Imaz, 2014). This technology favors a change in the reproductive imaginary of lesbian couples to the extent that they no longer have to "settle" for being social mothers through legal and social arrangements, and can be mothers "like any other couple" (Imaz, 2014). Behind these statements lies the desire not to be excluded from the social sphere and to resemble heterosexual couples. In this case, the centripetal force has won the conflict because it has managed to attract these couples towards the imaginary and the objectives of the system. In this process, the couple has cooperated with the system, sharing a reproductive imaginary and the system has adapted to a new type of users: lesbian couples.

This also shows the evolution of the imaginary of ART since it has shifted from exclusively targeting heterosexual couples to accepting a new type of users who brings along a new family model. Unlike the PHS, private clinics are companies that seek to maximise their economic benefits.[17] In this sense, reaching a new type of user is a good way to expand both their services and market. Private clinics adjust their company image (i.e., website, blog) to these changes in the environment because it allows them to broaden the spectrum of potential consumers. The use of ROPA method facilitates the reintegration of the difference in the nuclear family model. The technological system, far from being compromised, fulfills its function to the extent that it offers the couple a biogenetically linked child. In the case of lesbian couples who decide to use ROPA and in the case of those who persist in using AID and resist complying with the system (i.e., they have a high centrifugal force), both maintain a dependent relationship with ART. In the first case, they accept system's reproductive imaginary, while, in the second, at least one of them will maintain a kinship bond based on genetics, so that, in practice, they partially comply with system's imaginary. The only way not to depend on the system is to reject it.

Casuistry in the use of ART is very widespread since, in addition to the reproductive imaginaries of the users (system operators and end users), the medical condition of each patient must be taken into account. Frequently, the intentions or desires that underlie the imaginary cannot be satisfied in the way they were initially projected. This involves a process of negotiation and search through trial and error for the most appropriate technological fix. In these processes, the imaginaries of operators (embryologists, gynecologists, nurses) and patients (lesbian couples, heterosexuals, single women) may not coincide. Furthermore, reproductive imaginaries may change during the process, especially when patients have to overcome several failed attempts. In these cases, ART offers alternatives such as embryo adoption. The different technologies that constitute ART do not contribute equally to the main function of the system and may reinforce partially opposing imaginaries, especially when they are appropriated by unexpected users, such as lesbian couples. Despite this, an important reason why ART sponsors this type of practices is because, to a large extent, it is a business. Nevertheless, the imaginary of the system and its operators involves both the desire for patients to take home a healthy baby and the economic benefit of doing so.

Conclusions

In this paper I have analysed the role of reproductive imaginaries in the dynamics of technological change of reproductive technologies. First, I have explained this type of imaginary. I argue that reproductive imaginaries are collective visions of motherhood, infertility and kinship ties that are collectively maintained and carried out in the design and use of ART. These visions are dynamic and plural, so it is necessary to place them within social and cultural contexts. This facilitates the understanding of its plurality, even when divergences that are likely to enter into conflict coexist.

Subsequently, following Hughes, I have identified the phases of the structure of technological development in ART. In addition, I have shown the role of reproductive imaginaries in the process of co-production of ART and the environment in the different phases. System builders' imaginaries

played a decisive role in the invention phase of IVF and in establishing the function, but imaginaries that surpass Hughes' vision focus largely on the figure of great enterprising men. With the growth and transfer to other areas, the system continually ran up against reverse salients until it managed to consolidate itself.

Finally, in the fourth section I have explained the relationship between ART and its environment and how the system develops adaptations. The ART system and its environment are co-produced in dialectical processes through specific technologies. In these processes, tensions occur between the objective of the system and final users through centripetal and centrifugal forces respectively. Reproductive imaginaries and technical innovations are the means through which these negotiations and communication processes take place between the system and the environment. Thus, to continue exerting influence on its environment, the system adapts to integrate the elements of the environment and control them. If these elements were outside the scope of the system, they could not be controlled by it and the uncertainty would increase.

This case study suggests that applying co-production approach to LTS could be helpful to overcome the problem of the relation between the system and the environment, avoiding explanations in terms of soft determinism. Reproductive imaginaries have been shown to be explanatory tools of the reference frameworks that guide the technological practices of certain groups of users and operators and a key to a better understanding of the dynamics of LTS and their environment, providing a global perspective of change.

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Notes

1 ART refers to "all interventions that include the *in vitro* handling of both human oocytes and sperm or of embryos for the purpose of reproduction" (Zegers-Hochschild et al., 2017: 397), i.e., it includes *in vitro* fertilization (IVF). I will use ART to refer the system where IVF is included.

2 STIs are not the same as political agendas. Although both share normative prescriptions, STIs do not focus on defined and explicit objectives, so they are also less instrumental and politically responsible (Jasanoff and Kim, 2009: 123). They are also different from social values. STIs are ideas about what is desirable and, therefore, contain social values, but they include practices and courses of action that materialise those desires through institutions and social groups, as well as public actions (Jasanoff and Simmet, 2021: 2). Besides, STIs are not mere narratives or justificatory discourses of the science and technology that we have; they are rather the projections of possible futures through technoscience. They can be present in discourses and narratives, in the norms of a community and in metaphors and other cultural meanings. On the other hand, Jasanoff and Simmet (2021) emphasis the dynamic nature of STIs versus the static nature of actor networks.

3 See also the special issue "Symposium: The History of the first IVF births" at *Reproductive Biomedicine & Society Online* (2015).

4 Other case studies can help to understand the processes of negotiation between the system and its environment. For example, some ethnographies on egg freezing (Inhorn et al., 2022; van de Wiel, 2020) or studies on surrogacy (Smietana et al., 2018). For a systematic review of the main contributions of anthropology and sociology to the study of reproduction and ART, see Inhorn (2020).

5 Own translation.

6 ICSI requires sperm being selected and eggs being prepared by a biologist in the laboratory prior to the microinjection procedure, which is intended to induce fertilization. For a detailed description of ICSI, see Sara Lafuente (2017: 262-265).

7 In some men sperm formation is blocked. ROSI uses spermatids (cells with haploid genetic material in the phase prior to the final formation of the sperm) (see more in Tesarik et al., 1999).

8 Own translation.

9 See more about the ethical-legislative debates in the USA, Australia, Canada and Western Europe in D Melo-Martín (1998).

10 Data prepared by the author based on information collected from the 2002-2019 National Registry Reports on activities and results of assisted human reproduction centers and services (henceforth SEF Registry) and the National Commission for Assisted Human Reproduction Report (2022).

11 Own data developed from the SEF Registry.

12 For a broader view of the economic value of the global fertility market and global fertility chains see Vertommen et al., 2022.

13 Data from the SEF Registry.

14 It is different from sperm donation for many reasons. Between them, egg donation emerges in the context of IVF development and reaffirms its function. Sperm donation and artificial insemination by donor (AID) loses relevance in the context of the heterosexual couple with the development of IVF and, especially, with the introduction of innovations such as ICSI and ROSI.

15 Own translation.

16 Ovarian aging is one of the main causes of infertility in women in developed societies due to advanced maternal age (Agramunt et al., 2011: 129).

17 In contrast, the changes in public policies within the PHS have been motivated by the social and legal struggles of groups of discriminated women (Fernandez Jimeno, 2019).

Framed Uncertainty: Making Sense of Residential Wood Stove Emissions in Denmark

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Abstract

Residential wood stoves are often highlighted as the worst pollution source of $PM_{2.5}$ air pollution in Denmark, accounting for 52 percent of national emissions. This unambiguous number implies accuracy, and that researchers *know* how much $PM_{2.5}$ pollution can be attributed to residential wood stoves with precision. But we demonstrate in this article that emissions from wood stoves are notoriously uncertain and key parameters largely unknown. While the problem of wood stove emissions is often tied to the stove itself, this article illuminates the socio-technical assemblage surrounding wood stoves as an often overlooked aspect. Drawing upon discussions of uncertainty, we first show how knowledge about the socio-technical assemblage is constructed based on assumptions that emerge from domains of imperceptibility. Second, we argue that kindling practices can be understood as a kind of uncertainty which cannot be known with any degree of probability. To make better sense of wood stove emissions in public policy, we propose a 'framed uncertainty' lens to highlight the particular kind of uncertainty associated with key parameters in the socio-technical wood stove assemblage. Finally, we discuss the implications of changing the policy frame towards the socio-technical assemblage surrounding wood stoves in terms of reducing emissions.

Keywords: Residential Wood Stoves, Uncertainty, Emissions, Socio-Technical Assemblage, Air Pollution

Introduction

Air pollution researchers in Denmark claimed that residential wood stoves accounted for 52 percent of the $PM_{2.5}$ air pollution emitted in Denmark in 2019. This makes wood stoves by far the largest source of national particle pollution that is mostly associated with adverse health effects (Ellermann et al., 2022: 70). $PM_{2.5}$ pollution from wood stoves is often translated into absolute numbers regarding premature deaths and associated adverse health costs: 280 deaths and $0,7B, in 2020 (Ellermann et al., 2022). Journalists and pundits often use these numbers as a springboard for either shaming wood stove users, enforcing higher wood taxes, or calling for a total ban (Ankerstjerne, 2022). The detractors, in other words, appear to know exactly how much $PM_{2.5}$ pollution can be attributed to residential wood stoves, communicating accurate and unambiguous numbers

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(Funtowicz and Ravetz, 1990: 83–84). Emissions from wood stoves are, however, notoriously uncertain, and key parameters impacting emissions are largely unknown, we argue. In addition, 79% of the total air pollution in Denmark presumably originates from foreign sources beyond Danish borders, which means that Danish wood stove emissions actually only account for 6% of the total pollution in Denmark (Ellermann et al., 2022: 13). While the problem of wood stove emissions is typically tied solely to the appliance technology – the wood burning stove – this article examines wood stoves as a socio-technical assemblage – an aspect that is often overlooked in public debates, rendering the level of certainty less pronounced. This assemblage includes kindling and refilling practices – such as the size and quality of the pieces of wood loaded, as well as how full the chamber is made compared to its capacity – and ambient air conditions, both indoors and outdoors. It is vital to know these parameters when trying to make sense of wood stove emissions.

To shed light upon these largely unknown parameters we take inspiration from a recent upsurge in discussions of uncertainty (Beckert and Bronk, 2018; Hubbard, 2020; Jasanoff, 2018, 2022; Mehta and Srivastava, 2020; Scoones and Stirling, 2020; Stirling, 2023; van der Sluijs, 2016). Particularly within STS, economics, and sociology, the work demonstrates how our contemporary epistemic situation is defined as much by what is not known as by what is known. Rather than downplaying knowledge that is not known with certainty, this emerging body of work powerfully demonstrates how issues ranging from environmental hazards to economic futures and bureaucratic practices are shaped by different kinds of uncertainty. While uncertainty is particularly consequential at the science policy level (Jasanoff, 2022) this article focuses on those parameters in the residential wood stove emissions model that are least known.

We demonstrate that assumptions and uncertainties associated with kindling practices and socio-technical wood stove assemblages are particularly dominant phenomena in the subfield of air pollution modelling concerning residential wood stove emissions. To make better sense of residential wood stove emissions in public policy, we propose a 'framed uncertainty' approach to communicating estimates. Inspired by Jasanoff (2005) and Knight ([1921] 2018), this notion draws attention to the socio-technical assemblage surrounding wood stoves and the policy implications of the information that is unmeasurable, and that lies at the boundary of what is known and not known. To do this, we initially outline how the 'uncertainty' entails several gradations, or degrees, of certainty. We argue that average emission estimates are based on assumptions emerging from imperceptible domains, which are located beyond the reach of contemporary measurement regimes (Murphy, 2006). We then demonstrate how kindling practices can be understood as a kind of uncertainty which cannot be known with any kind of realistic probability (Knight, [1921] 2018). We conclude by discussing the public policy implications of our findings in relation to the unambiguous numbers highlighted above as well as the advantages of using the notion 'framed uncertainty' to make sense of emission estimates.

Method

To study how natural scientist produce wood stove emission estimates, we first consulted written material such as newspaper articles and policy documents to understand how the problem of wood stove emissions is being problematized in public discussions by different stakeholders. Second, we conducted semi-structured online interviews through 2020 – 2022 with a chimney sweep and 15 senior air pollution researchers. The interviews lasted approximately one hour each and were conducted mostly online via Teams or Zoom while Denmark was in different stages of lockdown during the COVID-19 pandemic. The researchers have expertise in different branches of air pollution modelling related to wood stove emissions, including emissions accounting and epidemiology. The researchers were selected as they contribute with different insights to the complex modelling process of estimating wood stove emissions. This also accounts for Danish chimney sweeps who provide key data to the researchers. The interviews enabled us to understand that key parameters surrounding the socio-technical wood stove assemblage are associated with different

magnitudes of uncertainty. We have subscribed to the research ethics protocol for collecting data with human respondents as outlined by the American Anthropological Association (2023) and follow the General Data Protection Regulation (GPDR) and the Danish Code of Conduct for Research Integrity, including anonymizing all informants (Ministry of Higher Education and Science, 2014).

Coping with unmeasurable uncertainty

Research on uncertainty has grown substantially within STS, economic sociology and economics (Beckert and Bronk, 2018; Best, 2008; Callon et al., 2009; Doganova, 2018; Haldane, 2018; Jasanoff, 2022; Kay and King, 2020; Pindyck, 2022; Tanzi, 2022; van der Sluijs, 2017). These scholars have demonstrated how the notion of uncertainty is essential for understanding contemporary issues like economic modelling and discounting, scientific policy advising and not least urgent environmental problems. To better understand how the question of uncertainty is being accounted for in the emission model for residential wood stoves, we draw upon the work of economist Frank Knight ([1921] 2018) and STS scholars Sheila Jasanoff (2005, 2018, 2022) and Michelle Murphy (2006). First, we outline the distinction between measurable and unmeasurable uncertainty as proposed by Knight (2018), which is underappreciated not only in mainstream economics but also in the analytical capacities of modern states (Jasanoff, 2012). Then we show why knowledge associated with unmeasurable uncertainty is typically located in domains of imperceptibility (Murphy, 2006).

When assessing the literature on uncertainty across disciplines we find numerous interpretations of the concept and no agreed upon definition. However, learning from Hubbard (2020), we can generally distinguish between a natural science version and a social science version of uncertainty. Whereas scholars trained in the natural and technical sciences tend to subscribe to the view that uncertainty ought to be rendered knowable through calculative endeavours (Aven, 2014, 2019; Hubbard, 2010, 2020), researchers trained in STS and social science tend to subscribe to the view that uncertainties often cannot be reduced to quantifiable measures due to inadequate knowledge. The latter argue that topics associated with high uncertainty are often being mistakenly reduced to unambiguous quantitative measures across a variety of disciplines ranging from climate and disease modelling to finance and macro-economics (Beckert and Bronk, 2018; Jasanoff, 2022; Kay and King, 2020; Scoones and Stirling, 2020; Stirling, 2023). Rather than invoking precision when such knowledge in unobtainable in practice, these scholars suggest that public policy could benefit from a much stronger acknowledgement of uncertainty. In agreement with the social scientists, this article demonstrates why key parameters of the socio-technical wood stove assemblage are indeed unquantifiable due to insufficient knowledge and lack of data.

The most useful definition of uncertainty for our purpose, was developed by economist Frank Knight, who distinguished between 'risk' and 'uncertainty' or what he also calls *measurable* and *unmeasurable* uncertainty. In a situation characterized by 'measurable uncertainty' the distribution of an outcome is known through either statistics or calculation, what is commonly understood by the term 'risk.' In a situation characterized by 'unmeasurable uncertainty,' on the other hand, Knight argues that it is impossible to form a group of instances, because the situations being dealt with are in a high degree unique (Knight, 2018: 233). Situations characterized by being unique are, in other words, associated with unmeasurable uncertainty because there is no scientific basis on which to form any calculable probability (Kay and King, 2020:13). Only the heroic entrepreneur could steer his business through situations characterized by uncertainty, Knight suggested - and this led him to point out that radical uncertainty gives opportunity for entrepreneurship, which has since been key to understanding economic, technological, and social progress (Kay and King, 2020). Knight's contemporary, John Maynard Keynes (2016), defining uncertainty along similar lines, homes in on situations where probability "is unknown to us through our lack of skill in arguing from given evidence" (Keynes in Beckert, 1996: 808). This, he adds, is when the evidence "justifies a certain degree of knowledge, but the

weakness of our reasoning power prevents our knowing what the degree is" (Keynes in Beckert, 1996: 808). Knight's definition of 'uncertainty' has been criticized for going against the natural science understanding of this term, where 'uncertainty' is thought to be an issue which can be determined numerically through a set of probabilities assigned to a set of possibilities (Hubbard, 2020:110). However, despite this criticism and lack of agreement between the natural and social sciences concerning the term, we find Knight's insights concerning unmeasurable uncertainty particularly apt for our purposes as we demonstrate below.

The conflation of risk and uncertainty is problematic for several reasons and yet particularly prominent in what Jasanoff (2012: 178) calls the analytic capacity of modern states, or 'technologies of hubris.' These technologies include cost-benefit analyses, climate models and risk assessments – all deployed by governments to manage areas characterized by high uncertainty in the Knightian sense. Although such modelling systems obtain their authority through disciplined approaches to analysis combined with claims of objectivity, they suffer from several deficiencies, especially regarding uncertainty and ambiguity. First, they downplay whatever falls outside their techno-scientific frame and second, they overstate whatever falls within (Jasanoff, 2012). The remedy, according to Jasanoff (2018: 13), is to complement 'technologies of hubris' with 'technologies of humility.' This framework revolves around foregrounding uncertainties and asking whether a problem needs to be reframed considering high uncertainties. Since uncertainties are particularly consequential at the science-policy intersection, public policy could profit from a much more thorough and genuine acknowledgment of uncertainty, she argues (Jasanoff, 2022).

While Knight and Jasanoff highlight that uncertainty is associated with a condition of incalculable probability (former) and largely ignored by the analytical capacity of modern states (latter), we also need to make sense of the phenomenon spatially. To better understand where uncertainty is located spatially in the context of modelling residential wood stove emissions, we draw upon Michelle Murphy's influential work. In her study of the 'sick building syndrome,' Murphy (2006: 9) takes the discussion of uncertainty to indoor environments and locates it in 'domains of imperceptibility,' where the subjects and objects of scientific research are rendered "measurable, quantifiable, assessable, and knowable in some ways and *not others*". Examining the history of how certain objects become knowable, Murphy demonstrates how this process is intrinsically tied to how other objects come not to exist, or come to exist only partially, with uncertainty or ignorance. In her case, chemical exposures from buildings were linked to the tangible practices of how lay people and scientists decided to render specific chemical objects such as particles knowable in specific locations and *not others* (Murphy, 2006.). We use this notion to illuminate how *assumptions* in the emission model emerge from processes of establishing knowledge from domains of imperceptibility.

Before demonstrating how the distinction between measurable and unmeasurable uncertainty is neglected in the wood stove emission model, we examine how assumptions about key parameters emerge from unknown domains such as domestic house practices.

Constructing numerical assumptions based on imperceptible domains

The role of uncertainty as well as the nature of the scientific assignment at hand was mostly clearly articulated by an air pollution researcher:

> The task is to produce an emission estimate which represents the reality in the best possible way. That is incredible hard because of all the uncertainties. But that is nonetheless what we must deliver. That is the task [given by public officials].

In other words, the goal is to offer a number. An estimate, but nonetheless a number. Each year, air pollution researchers thus calculate the amount of $PM_{2.5}$ pollution that is being emitted by residential wood stoves in Denmark to comply with the Convention on Long-Range Transboundary Air Pollution (Nielsen et al., 2021). The preferred method for measuring particulate matter (PM) emissions factors from different types of resi-

dential wood stoves is called the 'dilution tunnel' method. Here, using a dilution tunnel about a meter from the chimney, the number of condensable particles from smoke gases are measured as they cool down. This method, used mainly in Norway and Denmark, contrasts with approaches – such as the European standard (EN13240) – that measure particles directly in the hot smoke gases within the chimney (Nielsen et al., 2021) without reference to condensable particles. A researcher interviewed said that the results garnered by the two methods can vary by anything from factor 2.5 to factor 10. The implication of this variance is that a country like Germany, for example, seems to have much lower emissions compared to Denmark, when in reality, because their methods are so different, their results are incommensurable, the researcher elaborates. Yet even though air pollution researchers clearly acknowledge the high uncertainties associated with the different measurement methods, they do not specify the magnitude of uncertainty that is associated with them in the emission model (Nielsen et al., 2021).

Residential wood stoves are as diffuse a source of emissions as cars. Yet, the official data inventory for personal vehicles is much more comprehensive, accurate and elaborate due to political attention on road traffic across several decades. Most countries require that road vehicles are registered via license plates. Interested parties can thus look up key features of any vehicle in the Danish vehicle registration database such as how large the motor is, what tires are equipped, how far it drives per litre of gasoline, roughly how far it has driven in total, which filter is attached to the vehicle following Euronorm standards. For the residential wood stove sector, equally important data is either absent or must be pieced together from disparate sources, such as sample studies, laboratory measurements, and, not least, assumptions.

In an interview, an air pollution researcher compares wood stoves with powerplants to show how difficult they are to make sense of:

> The unfortunate thing about residential wood stoves is that emissions will always remain uncertain by nature because we are talking about, you know, a thing that is situated in the living rooms of people. One thing is a powerplant, which has one chimney. It is super easy to measure. But we have 700.000 residential wood stoves, and of course it is not realistic to measure emissions from these appliances all the time. […] There is uncertainty regarding how many old stoves are there, how many new stoves are there, and how much firewood is being consumed in the old compared to the new ones. The implication is that there are many assumptions [in the model], all of which are uncertain.

While researchers are unable to measure emissions directly from Danish residential chimneys, they follow the air pollutant emissions guidebook of the European Environment Agency (2019). Average emission estimates are thus based upon laboratory measurements combined with smaller sample studies of in-situ measurements of different technology appliances where researchers try to consider and replicate the many parameters and user practices which impact emissions.

The situations that air pollution researchers simulate to measure emissions include combustion of wet and dry wood, part load and full load, as well as common misuse situations (Nielsen et al., 2021: 37-38). A key difficulty concerning firewood consumption pertains to the fact that a lot of wood is not sold via official markets, in contrast to gasoline and diesel consumption, which is registered in official databases. Some people collect their own firewood in forests or process it on their own property, which means that knowledge regarding the quality of firewood is unobtainable. Researchers are aware that burning different species such as pine, birch or beech leads to different emissions but, as one interlocutor told us, data at this level of detail is unobtainable. To construct an average assumption about the quality of firewood, researchers take into consideration that there is a spectrum from moist to dry. Based on assumptions about the moisture level in wood logs, researchers try to estimate an average emission level, which they assume to be the mean value. The assumed humidity level of wood logs in the emission model has consequently been set to 15 percent (Nielsen et al., 2021: 39), but the real conditions are unknown. Meanwhile the unit consumption of all wood stoves is considered equal (Nielsen et al., 2021: 13), although it differs across geographical regions and ignores catego-

ries such as inner-city apartments, suburbs, rural houses, and, not least, technological appliances. Assumptions about the quality of wood logs, in other words, emerge from a domain that is imperceptible (Murphy, 2006: 9), where scientific objects are rendered knowable via assumptions or expert judgments, as the researcher highlights above.

The study of wood stove pollution has been approached via a wide range of methods. Between 2005 – 2013 air pollution researchers collected data on wood consumption via phone sample interviews. This method was changed to online survey samples from 2015. Based on biannual surveys that have been carried out by different companies (Force Technology and Ea Energy analysis) for the Danish Energy Agency, the researchers estimated how wood consumption evolved over time since the first survey was carried out in 2005. From 2007 to 2017 firewood consumption apparently remained relatively stable in Denmark at approximately 25 PJ (petajoule) (Nielsen et al., 2021: 15). One researcher we spoke to notes that they will probably never know the consumption of firewood before 2005, there simply is no data.

Current calculations are moreover based on assumptions about worst-case and best-case user behaviour and assumptions about the quality of the wood they burn. The goal is to construct bottom-up average emission estimates for the approximately 738,000 residential wood stoves and 'other appliances' that are not too far from the actual emissions, a researcher elaborates. However, uncertainty is omnipresent in the emissions model. There is uncertainty associated with the very term 'wood stove,' as the emissions data also includes a number of 'other appliances' such as open fireplaces, pizza ovens, garden fire pits, barbecue grills, and sauna ovens (Nielsen et al., 2021: 31). The researchers' estimate of "wood stove emissions" in essence does thus not just originate from wood stoves. Although emission levels from 'wood stoves' and 'other appliances' show great variability depending upon the quality of the wood loaded, the kindling practices, and the load capacity of the appliances, the researchers do not go into detail describing the impact of uncertainty that is associated with these parameters (Nielsen et al., 2021: 69). In other words, expert assumptions about these key parameters emerge to a large extend from domains that are imperceptible (Murphy, 2006) due to the dearth of data and large-scale measurement campaigns.

Researchers collect data on the number and age of appliances from the Association of Chimney Sweepers (DAPO), and data on wood consumption is collected via sample surveys done by the Danish Energy Agency every second year (Danish Energy Agency, 2019). Sales figures for residential wood stoves are not publicly registered. A time series has therefore been constructed based on assumptions and information obtained from the association for suppliers of fireplaces and wood stoves (Kristensen, 2019 in Nielsen et al., 2021:12). Data on annual scrapping of old stoves is likewise not publicly available, and the researchers behind the emissions model have therefore constructed a replacement curve, under the assumption that most stoves are being replaced on average after 30 years (Nielsen et al., 2021: 12). This relates to a recent regulation compelling owners to replace stoves that were installed before 2003 (Ministry of the Environment Denmark, 2022). In addition to receiving quantitative data from different sources, researchers benefit from asking chimney sweepers conversationally whether they are seeing more woodburning stoves being established than dismantled, and other questions that give a sense of how the sector is evolving. While annual figures for scrapping of old stoves is unknown, researchers *estimate* a growth rate of around two percent in the number of woodburning stoves in use for the whole sector, based on *assumptions* about the replacement of old stoves and sales data from DAPO (Nielsen et al., 2021: 28). Due to these difficulties in obtaining reliable and accurate data, emissions are thus usually less well-known compared to large-scale energy production, vehicular traffic, and most other emission source categories, and accurate and reliable assessments of residential wood stove emissions therefore remain a challenge in many countries (Kukkonen et al., 2020: 4350-4351).

This section has demonstrated how the construction of knowledge regarding emission estimates for residential wood stoves is intimately linked to expect judgments due to the absence of empirical data. It unfolds in the form of assump-

tions about 1) the quality of wood that is being burned (moisture content and species), often varying according to geographical location; 2) the size of the load compared to the capacity of the appliance; 3) firing techniques; and 4) expected lifetime and replacement rates of wood stoves. These assumptions derive from locations that resemble domains of imperceptibility (Murphy, 2006: 9) where information regarding the socio-technical wood stove assemblages is rendered numerical through expert judgments rather than empirically determined facts. In other words, estimates of wood stove emissions are less tied to the actual emissions of the approximately 738.000 wood stoves and other appliances in Denmark; rather, they are produced based on *assumptions* about socio-technical wood stove assemblages that shape simulated experiments and associated measurements in laboratory settings. The validity of the incumbent estimates can easily be questioned based on competing interpretations of assumptions, as we show in the section below, where we proceed with a focus on the actual use of the stove, more particularly how kindling practices shape levels of uncertainty regarding emission estimates.

The unmeasurable uncertainty of kindling practices

One of our interlocutors, a professor specialized in the adverse health effects of air pollution, succinctly captures the extent of the enigma facing researchers studying how the different appliances are operated and what is being burnt:

> Do wood stove owners burn wood? Is the wood they burn dry or wet? What else do they burn besides wood? Paper, cardboard, coke, or pizza trays? If they use wood, how do they light the fire? Using paper or fire starters? How do they air-condition? Do they put the right amount of wood into the oven? Do they burn overnight?

In other words, there are many factors that need to be considered when understanding air pollution from woodburning stoves. Burning wood overnight with little inflow of air to preserve embers for the next day, the professor notes, is for example one of the worst things users can do to the environment. Similarly, burning wet wood produces far more particles than dry wood. There is currently a lack of comprehensive studies about how user behaviour impacts emissions from residential wood stoves (Reichert et al., 2016: 246), which leads us to the more fundamental question of how a wood stove should be operated to avoid high discharge of particles.

A chimney sweep, who is engaged in the particle pollution debate in Denmark, believes the correct firing technique is key to clean combustion processes. He claims wood stove owners can eliminate up to 80 percent of the particle discharge by igniting wood logs via a so-called top-down ignition method (Andersen and Hvidberg, 2017: 70). The theory behind the top-down kindling approach is that gases originating from lower-lying wood logs in the combustion chamber are ignited by the flame at the top like a candle, the chimney sweeper explains. On top of a couple of wood logs, users should place 12-14 small wood sticks before starting the combustion process with a few starters placed on top of the small wood stick pile. While the 'correct' amount of wood loaded in the combustion chamber depends on the specific requirements of each appliance, a rule of thumb holds that the size of the firewood pieces should not exceed the size of a forearm, the chimney sweeper elaborates. The moisture level of the wood log should not exceed 18 percent. Then, a fire needs oxygen to burn properly. Depending on the appliance, a wood stove must also be supplied with sufficient air from its surroundings. Under these conditions, a fire will burn its way down through the pile in a relatively clean combustion process if the wood is sufficiently dry, according to the top-down approach.

If, on the other hand, a wood stove user ignites a fire via the bottom-up approach, the flame cools as it ascends through the different layers of wood. This leads to an increase in particle discharge due to poor combustion of gases, the chimney sweeper continues. One way of determining how clean the combustion process is, is to go outside and examine whether any visible smoke is coming out of the chimney. While some smoke is unavoidable, especially during the ignition phase, smoke from the chimney should

barely be noticeable after 10-15 minutes under ideal combustion processes. Lighting a fire via the top-down approach with dry wood is, in other words, a good starting point for lowering particle discharge (Andersen and Hvidberg, 2017).

Several uncertainties concerning air conditions, the quality and amount loaded in the appliance and not least, kindling practice are raised by the chimney sweeper's top-down approach to kindling. How do researchers know which approach is more common among Danish wood stove users, let alone if users burn objects other than wood? An air pollution researcher outlines why knowledge about kindling practices is unobtainable for the time being:

> We do not know, and it is incredibly hard, as there are some who use it [the residential wood stove] a lot, some use it less, some are good at it [kindling a fire], some are bad. Some burn anything that can be burnt, whereas others use proper dry wood logs. So, the variability is enormous.

While researchers who have constructed the residential wood stove emissions model do not go into detail describing the impact of the uncertainties surrounding key parameters outlined in this section (Nielsen et al., 2021: 69), we argue that the heterogeneity of the situations prevents the researchers from managing uncertainty via calculative endeavours (Knight, [1921] 2018: 135-136). That is, there are fundamental uncertainties involved in the situations researchers are trying to simulate because each socio-technical assemblage surrounding each wood stove – firing practice, moisture levels, quality and size of load in the appliance, and air conditions – is unique. Emission estimates, in other words, are merely estimates, to follow Knight (2018), which implies that there is no possibility of forming quantitative determinations of probability associated with them, or any degree of measurable uncertainty.

To summarize, this section has demonstrated how the uncertainty associated with kindling practices can be understood as a kind of unmeasurable uncertainty in the Knightian sense ([1921] 2018: 135-136), as researchers arguably cannot configure quantitative determinations of probability associated with kindling practices and their associated socio-technical assemblages. Having established this vantage point for understanding residential wood stove emissions is, however, inadequate in and of itself in relation to making emissions reductions actionable in the current policy frame.

Framed uncertainty

The incumbent public policy tradition assumes that solutions to complex environmental issues like wood stove emissions need to be determined by precise quantitative statements and that numbers alone are a sufficient means of policy input (Funtowicz and Ravetz, 1990; Jasanoff, 2018). The unique relationship between public officials who expect that scientists can deliver precise answers on the one hand, and on the other hand, researchers who are constantly facing large uncertainties in their everyday work, results in discussion of uncertainty taking a backseat in science conducted for policy. However, the suppression of uncertainty is problematic because it obfuscates what is going on in science while simultaneously preventing public officials from seeing which scientific topics, locations or objects need to be researched in the future to improve the knowledge foundation for science and public policy. Informed by Knight (2018), we have demonstrated how air pollution scientists handle the uncertainty associated with key parameters in the production of wood stove emission estimates. That is, they turn expert assumptions into numerical values and thereby conflate an unmeasurable uncertainty with a measurable uncertainty that can be estimated with a degree of probability. Based on this operation wood stove emission estimates are now conveyed in the form of an unambiguous number (52%) although there is no basis on which to establish any degree of calculable probability with this number. In other words, due to the incumbent public policy tradition researchers are compelled to come up with a number – and one number only - whose associated uncertainty appears unacknowledged.

Inspired by Jasanoff (2005; 2018) and Knight (2018) we propose an alternative approach to communicating wood stove emission estimates and their associated uncertainties at the science policy level. This approach dismisses the idea that

solutions to complex problems like wood stove emissions must be determined solely by quantitative facts. Rather than trumpeting accuracy, we propose a 'framed uncertainty' approach which implies an analytical and normative dimension. First, the analytical dimension highlights that wood stove emission estimates are merely estimates in the Knightian sense because there is no basis on which to form any degree of measurable uncertainty. This is because kindling practices and their associated heterogeneous socio-technical assemblages are in reality quite unique as we have outlined in detail above. Second, drawing upon Jasanoff's (2022) plea for humility, 'framed uncertainty' involves accepting uncertainty as the foundation for public policy while making harm mitigation a goal because uncertainties are particularly consequential at the science policy intersection. It suggests that the incumbent policy frame needs to be continuously questioned to draw attention to whatever falls outside the frame.

Drawing upon actor-network theory, Jasanoff demonstrates the contingency of a particular policy frame by highlighting how traffic accidents, which were once perceived as random accidents involving typically young people and teenagers, were at a certain time in American history reinscribed in the national consciousness as drunk driving. To illustrate this point Jasanoff invokes Gusfield's (1997) account of drunk driving by emphasizing the socio-technical elements of driving. As the frame of social attention shifted away from random accidents, the car emerged as a socio-technical assemblage tied to hard and soft components including practices, objects, rules and actors all entangled in complex networks of transportation (Jasanoff, 2005: 24). The impact of the novel policy frame on car accidents is worth citing at length:

> As if endowing its users with x-ray vision, the frame of drunk driving permitted society's movers and shakers to detect all kinds of once invisible nodes in the network where intervention now seemed possible in the interest of saving lives: raising the drinking age; penalizing innkeepers and even private party-givers who allowed drinkers to go on the road; mandating seatbelts use; reducing speed limits; and requiring cars themselves to be engineered with new safety features such as airbags and antilock brakes. (Jasanoff 2005, p. 24)

As the different elements of the socio-technical car assemblage became obvious to public officials, it produced a novel regime of safety regulation surrounding the car (Jasanoff, 2005), she emphasizes. In other words, attending to the way in which a particular issue is framed under circumstances of high uncertainty, pays off when it comes to analysing scientific uncertainties at the science policy level (Jasanoff, 2018: 13). Akin to Jasanoff's insights above, our analysis allows us to propose that wood stove emissions emerge from heterogeneous socio-technical assemblages tied to soft and hard components including firing techniques, indoor and outdoor air conditions, wood moisture, load in the appliance and of course the wood stove technology in itself. By stressing that emissions are determined by the interaction between users and their heterogeneous socio-technical wood stove assemblages, this approach to understanding woodstove emissions provides policymakers with opportunity to intervene and regulate emissions in new ways.

While combustion of wood in residential wood stoves undoubtedly leads to outdoor emissions, novel sample measurements of indoor particle discharge point toward a hitherto overlooked problem. Sample studies are few and small in scope (Bruun, 2022; Jensen et al., 2012; Olesen et al., 2010) but collectively, they demonstrate that indoor environments often become polluted with particles during combustion processes. Indoor particle discharge typically occurs during the early ignition phase, when firewood is combusted in a cold oven, with slightly open oven door (Olesen et al., 2010). Opening of wood stove levers during refills, sudden wind blows, use of ventilation systems or extractor hoods can also contribute to indoor particle discharge (Jensen et al., 2012: 45). A common theme for these studies is that significant spikes of particle discharge typically occur during the kindling and refilling phases when the lid of the stove is open. Discharge of particles into living rooms is potentially more dangerous, as particles are emitted directly into the living rooms of wood stove users and not mixed with outdoor air. When harm mitigation is the goal of communicating about wood stove estimates to public officials, then the implication of these emerging studies is that the incumbent policy

frame centred on outdoor emission ought to be complemented with an acknowledgement of those indoor particles that fall outside its current scope of vision. By acknowledging the likely dangers of indoor particle discharge, an emerging issue which needs to be uncovered through large-scale measurement campaigns, the limitations of the current policy frame can be conveyed to policymakers.

In summary the 'framed uncertainty' approach to communicating wood stove estimates at the public policy level draws attention to the unmeasurable uncertainties associated with key parameters in the socio-technical assemblage surrounding the production of wood stove emissions estimates. It highlights that estimates are merely estimates in the Knightian senses because there is no basis on which to form any calculable probability. More importantly by accepting uncertainty as the foundation for public policy while having harm mitigation as a goal, this approach to communicating wood stove emissions to public officials stresses the limitations of the incumbent policy frame by foregrounding those particles and practices that fall outside its scope of vision.

Conclusion and public policy implications

Although our analysis has focused on how uncertainty is an integral part of the science of air pollution, our point is not to relativize the scientific output of researchers. On the contrary, it is to highlight that the researchers are fully aware of the many uncertainties implicated in their studies. Yet, they are also under pressure to comply with politically determined regulations. In that process they produce specific answers and unambiguous numbers concerning how much residential wood stoves contribute to national $PM_{2.5}$ pollution – the 52 percent. The proliferation of precise numbers in public discussions of wood stove emissions, premature deaths and associated costs, however, do not resonate with the reality, which is far more nebulous, unmeasurable, and unknown, as we have shown. In other words, our analysis demonstrates that the knowledge foundation for having public discussions about unambiguous wood stove emission estimates rest upon a fragile house of cards built on unmeasurable, uncertain assumptions. It is a house of cards that is not wrong, but it is solely based on elements that to some extend can offer an exact number. The implication is that in efforts to reduce particle emissions, the wood stove is targeted, albeit, in reality, the researchers' "emission estimate" encompasses a much wider category of other appliances not encompassed by the policy. By trumpeting accuracy in discussions of wood stove emissions public officials fail to recognise that emissions are intimately entangled with user practices and the socio-technical assemblage surrounding stoves and that 'wood stove emissions' are likely also on indoor issue.

Whereas incumbent public policy responses to reducing emissions are focused on technological fixes and economic incentives, the implication of our analysis is that there are ample opportunities to reduce emissions by also focusing on the interaction between users, stoves and the heterogeneous socio-technical assemblage surrounding stoves. Rather than trumpeting accuracy when there is none – and in reality, cannot be any – we argue that it is more helpful to make sense of wood stove emissions through the lens of a 'framed uncertainty' when conveying estimates to public officials. This approach embraces the high uncertainties as the foundation for policy responses. Rather than limiting policy responses to technological fixes and taxation, our study offers opportunity to regulate emissions in new ways by focusing on the practices and interactions between users and stoves to save lives while accepting that such policies are applied without the possibility of determining emissions with accuracy.

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Stengers Isabelle (2023) Virgin Mary and the Neutrino. Reality in Trouble. Translated by Andrew Goffey. Durham and London: Duke University Press. xii, 250 pages. ISBN: 9781478025207

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What's the difference between the Virgin Mary and a neutrino? This reads like the set-up for a Christmas cracker-worthy joke. In Isabelle Stengers' work, however, the question is of weighty significance, serving as the point of departure for the analysis of one of the most fundamental problems of being in the world. In the secular modern era, the existence of neutrinos is accepted because a scientific apparatus has been created that can reliably prove that the particle is, in fact, part of the fabric of reality. The Virgin Mary, in contrast—alongside other supernatural beings such as ghosts, djinns, demons and spirits—is relegated to the sphere of belief, and thus classified as non-existent. In this schema of thought, the neutrino objectively exists, whilst the Virgin Mary exists only as the subjective creation of Catholic believers. Stengers challenges the intellectual status quo with the contention that the Virgin Mary and neutrinos both objectively exist, though they do so rather differently.

In dialogue with Bruno Latour's work, Stengers develops a way of thinking about various beings in the world that accords them different 'modes of existence' (Latour, 2013; Stengers and Latour, 2015). Both the Virgin Mary and neutrinos form part of our reality because they *matter* to religious practitioners and to scientists respectively. They belong to reality in very different ways, however. In the scientific domain, a neutrino needs a chain of 'reliable witnesses' to exist and an extensive experimental apparatus to be 'conjured'. In the religious sphere, the Virgin Mary is revealed to believers through processes of spiritual transformation, such as pilgrimage, that oblige physical and mental preparations. The scientific particle can be made to appear at will, provided the right experimental conditions: proof of its existence is reproducible, reliable. This is in stark contrast to the Virgin Mary. As a religious being, her visitation—proof of her existence—can never be guaranteed. Believers may invoke her, but that does not necessarily mean she will appear. It would be preposterous to attempt to prove the existence of a neutrino through a spiritual ritual. It follows, then, that we should not try to prove the existence of the Virgin Mary through scientific inquiry. This amounts to a category mistake on a par with attempting to capture an image with a sound-recording device.

In a somewhat counter-intuitive manoeuvre, Stengers establishes the intrinsic differences between neutrinos and the Virgin Mary in order to dissolve typical binaries of thought, such as science vs. religion, rationality vs. irrationality, and objectivity vs subjectivity. Such binaries function as intellectual obstacles to the appreciation of the value and specificity of scientific practices, a core axiom in Stengers work and, indeed, in Latour's. In her reading, scientific practice is dissimilar to all other practices, *pace* relativist approaches of the social constructivism of the late 1990s. This is because, for Stengers, "[n]o practice is like any other" (p. 101). Every practice is *among other practices*—legal, political, ethical, technological. It is unique in the specific obligations it imposes

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on its practitioners, and in the specific actions required to enact it but it is one of many other practices that exist. Importantly, the intrinsic heterogeneity of practices must be duly recognized if we wish to describe well all the various beings that matter to us in this world, be they natural, fictional, spiritual or technical.

By turning to beings belonging to spheres that are set at radical opposition in our modern world—religion and science—Stengers opens up new and richer ways of relating to the world. In particular, she leverages the work of ethnopsychiatrist Tobie Nathan (2001) to demonstrate that humans are not alone in the world. This is what the 'cosmo' in Stengers' coinage of 'cosmopolitics' stands for. The philosopher's cosmopolitical approach allows us to attend to the vast array of beings that are meaningfully part of our worlds—from fictional characters to drugs, smartphones, and even the dead—and to find ways to articulate them that are consistent with their unique modes of operation. Such articulation is important because it gives us the tools to understand the elusive yet powerful beings that profoundly impact our lives. This equips us with the ability to negotiate with them, and even protect ourselves from them if necessary.

In this context, Stengers speaks of an 'ecology of practices' as one way of tracing how we are affected by the various non-human entities in our lives and perceiving in more granularity precisely how they matter to us. 'Ecology' is understood here as an approach that would "associate heterogeneous protagonists pursuing divergent interests, united by relations that are not symmetrical, all protagonists making what unites them matter differently" (p. 81). Ecology thus marks the possibility of different beings and different modes of existence to creatively coexist with one another, without the necessity to fuse with each other or dominate one another. This approach does not aim to render religion more scientific (by looking for pieces of Noah's Ark on Mount Ararat, for instance) or science more spiritual (by delving into the divine messaging of cosmic bodies, for example). In the modern world, experimental-theoretical scientific practices have dominated our articulation of beings such as neutrinos, enzymes, and DNA. Such practices dismiss as non-existent all other beings that cannot be articulated in an appropriately scientific manner, including supernatural entities, spirits, ghosts, and so on. With an 'ecology of practices', Stengers offers a powerful alternative, through an interrogation of how existence is produced in specific modes. 'Practice' here is key: a practice is always anchored in a very particular milieu in which a being operates, rather than to any free-floating notion that circulates independent of its local attachments.

Virgin Mary and the Neutrino was first published in French in 2006 in the aftermath of the so-called 'science wars' in the USA, in which the nature of science (whether as a social construct or as a representation of reality) was subject to heated debates. It was translated seventeen years later with some modifications by the author. To be blunt, it is a tough read—both in terms of topic and expression. For a start, the book proposes a radical rethinking of our most basic Western and modern patterns of thought about science and religion, i.e. facts vs. beliefs. The opaque writing style muddies things further. Thinkers in Stengers' immediate intellectual circle, like Latour or Vinciane Despret, write in a more reader-friendly mode, taking pains to walk readers through the theoretical mazes constructed in their work. Stengers is not interested in such hand-holding that would allow readers to navigate the crucial intellectual conundrum she delineates. Readers must either be intimately familiar with the literature and debates to which Stengers refers throughout the book, or, ideally, have read Latour and Despret to fully grasp the stakes and the importance of the analysis at hand. For this reason, it is perhaps most fruitful to read this book together with other texts, notably those by Latour, Despret, Haraway, and Nathan—and treat Stengers' work here as an 'entangled flight' (Pignarre, 2023). What hasn't been directly expressed in this book, is most likely addressed, albeit with a twist, in Latour or Despret. Nevertheless, the intellectual entanglement evident in the book's argumentation does not make its core analytical thrust any less fascinating, thought-provoking or inspiring. On the contrary, it serves to unite an assembly of thinkers that resonate with each other and, thereby, reciprocally extend the remit of each other's works in a truly ecological way. In this volume, then, we witness how innovative intellectual endeavour always happens with and through others.

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Hennion Antoine and Levaux Christophe (2023) Rethinking Music through Science and Technology Studies. Abingdon & New York: Routledge. 304 pages. ISBN: 9780367767723

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In their edited volume, Antoine Hennion and Christophe Levaux have gathered a collection of scholarship that aims to help scholars understand the world of music by examining the intersections of its enterprises, objects, devices, techniques, theories, and practices. With their interdisciplinary entry points into STS, the contributors to the volume share their commitment to breaking free from the oppositions of objectivity and subjectivity, as well as machine and human, moving towards an approach to the study of music that focuses on the interaction of disparate socio-technical elements in production, consumption, and experience of music (p. 3). Together, the collection presents a comprehensive effort of rethinking approaches to the study of music towards frameworks that do not separate the human, the nonhuman, and the political. STS, here, is an analytical entry point, a departure into analyzing the different societal, political, structural, normative, material, and historical elements that make up the world of music.

The editors divide the book into four parts, combining scholarship on histories, instruments, technologies, and practices. In the largest part that focuses on histories, Fanny Gribenski explores how the note A became known as 'natural' pitch, while François Ribac traces DIY practices in recording technologies, positing them as continuous cultural phenomena rather than radical revolutions. Patrick Valiquet extends ANT to explore how the development of 'universal grammar' in music is enmeshed in political and epistemological imperatives of discourses around human rights. In the instruments section, researchers explore tools from early Moog instruments to the Eurorack synthesizer. The employment of STS-specific analytical frameworks to explore technological aesthetics (by Eliot Bates) and boundary work of instruments (by Paul Harkins) allows the authors to capture how the world of music arises from the interplay of technologies with historically contextual human practices in very specific environments.

Moving to discussing technologies and practices, the book takes a more conceptual turn. David Trippett and Nick Prior's contributions explore the relationship of humans and machines through a refreshingly, though not explicitly, co-productional lens that does not prioritize the logic of humans nor of machines. Basile Zimmermann develops a theory of materiality in the STS frameworks of SCOT and ANT in an ontological argument for studying music in the digital age. The final part of the volume takes seriously the materiality of human practices. François Debruyne grounds online exchanges, pushing the actor-network framework to trace how communities are made through, rather than because of, their communication. The focus on the reconstruction of publics through practices culminates in Jean-Paul Fourmentraux's theorization of the relationship between human and technical objects as one of continuous acquaintanceship. The volume

thus ends with an example of the kind of sociotechnical analytical framework the editors strive to develop - one that studies music practices as shapers of the world through interactions between humans, objects, and networks.

While the organization of the volume into the four parts is effective in thematically grouping the constructivist STS approaches, such a structure prevents the book from fully achieving its aim of presenting a sociotechnical research framework. Constructing its sections not by the empirical focus of the researchers (be it instruments, practices, histories or technologies) but by the methodological and theoretical approach of the chapters might have served this goal better. After all, as the editors point out, the unique contribution of STS lies precisely in the breaking of oppositions of objects of study and in the focus on the intersections between them. The sonic imaginaries that Mooney and Pinch develop, from this perspective, might have fruitful points of dialogue with Prior's negotiation of assemblage as the political stakes of imagined worlds are at stake in both chapters. Ribac's historical discussion of cultural practices and Trippett's cultural account of digital voices are both concerned with how music practices contribute to the articulation of the concept of the modern human. What might we learn not only about music but about the dissemination of information if we read Debruyne's attention to digital structures in conversation with Leech-Wilkinsons's exploration of religious networks in classical music? Placing the articles in relationship to each other based on the conceptual and epistemic stakes of their scholarship would show how the sociotechnical analytical framework the editors propose can not only improve music research but place music studies in a more direct relationship to the broader questions of the role of various artistic practices in the making of the modern world.

Some scholars criticize certain STS approaches for being too empirically oriented, arguing that social reality cannot be understood through empirical case studies alone (Collin, 2011). Appeals to the importance of non-STS theory have been made, including to political theory (Thorpe, 2008), dialectic approaches (Söderberg, 2021), and a return to structural concepts in understanding technology that already exist in organizational sociology and political economy (Klein and Kleinman, 2002). While the calls for conversations with non-STS theory are important, another part of the answer to this concern might be in the way that we as scholars engage with existing empirical work together. More than being about rearranging the typeset of a book, my emphasis on the structure within it would give STS scholarship the potential to produce rigorous analytical worlds – just like the different musical elements produce, rather than reflect, the world of music. Then, this book might be able to contribute more deeply to the further development of STS not only as an orientation but as a rigorous and replicable approach to studying the sociotechnical world.

Moreover, the editors of this volume chart the development of their sociotechnical approach as stemming largely from sociological and STS-related fields (p. 1-3). However, engagement with similar efforts from music studies might help contextualize this feat more accurately. While the book might be the first concerted effort to present the sociotechnical approach as applicable to a range of research topics within music, multiple scholars have previously come together in search of similar frameworks. Significant historical (Zagorski-Thomas et al., 2012) and socio-cultural (Mazierska et al., 2018) perspectives have provided productive, albeit limited, efforts of capturing a similar research program. Similarly, the special issue "Music knowledge and science studies" of the journal *Revue d'Anthropologie des Connaissances* (2019), co-edited by one of the authors of this book, served a similar goal of sculpting a body of work for the reflexive study of worlds of music. The need for the study of "the larger enterprise that constitutes the world of music" by entering into the many elements that inhabit them, as Howard Becker phrases it in his foreword (p. xvi), stems not only from the recent development of STS as a theoretical and analytical tradition, but also from the existing analytical connections between communities of interdisciplinary researchers who have been working in similar ways before this book. Greater engagement with such literature could help root the useful breadth of this volume within the existing archive of inquiries into the worlds of and around music.

While applying sociotechnical approaches to the study of musical phenomena is not entirely new, the extensively broad collection of scholarship in this volume presents an illustratively cohesive sociotechnical research approach to studying the co-constitution of the world of music through intersections of the human, the technical, and the societal. Although a more theoretically forward curation of this research program and greater engagement with existing scholarship might have helped the book develop this framework even further, the authors and editors do succeed at illustrating a comprehensive research approach that helps rethink the silos of music. A call for this effort in turn reflects the need for reflexive sociotechnical scholarship in social sciences that engages in the complexity of the modern more-than-human world and is at the same time deeply committed to developing analytically useful theory.

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