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Reflections on the Reversibility of Nuclear Energy Technologies

Reflections on the Reversibility of Nuclear Energy Technologies

Proefschrift

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In loving memory of Philip Serracino-Inglott,
a peer without equal and forever a friend.

Contents

Summary

The development of nuclear energy technologies in the second half of the 20th century came with great hopes of rebuilding nations recovering from the devastation of the Second World War or recently released from colonial rule. In countries like France, India, the USA, Canada, Russia, and the United Kingdom, nuclear energy became the symbol of development towards a modern and technologically advanced future. However, after more than six decades of experience with nuclear energy production, and in the aftermath of the Fukushima nuclear disaster, it is safe to say that nuclear energy production is not without its problems.

Some of these problems have their origins in the very materiality of the technologies involved. For example, not only does the use of highly radioactive materials give rise to risks for the current generation (e.g., in the potential for disaster when reactors melt down) but high-level radioactive waste from nuclear energy production presents a serious intergenerational problem for which an acceptable final solution or its implementation remains elusive. Moreover, nuclear energy technologies have specific social and political consequences. For example, they have been said to be authoritarian technologies (Winner, 1980), requiring centralized authority, secrecy, and technocratic decision-making.

While some of these problems could have been foreseen before nuclear energy technologies were introduced, others only arose after these technologies were already integrated into the social and infrastructural fabric of our lives. Additionally, new technologies (e.g., Generation III, III+ and IV reactors) are still being developed, bringing with them new and uncertain hazards and risks. Ignorance and uncertainty about the possible deleterious effects of introducing a new technology are inevitable, especially if the technology is complex, large timescales are involved, or risks depend on social or political factors unforeseen in the design stage. However, this should not deter us from developing and introducing new technologies. Rather, it should motivate us to organize these 'experiments' with new technologies in society in such a way that we can *learn* about their possible hazards and risks as effectively and responsibly as possible (van de Poel, 2011, 2015). In this way, it is possible to minimize risks and avoid unwanted moral, social or political developments. However, organizing such experiments responsibly also means that one could come to the conclusion that

continuing an experiment is no longer responsible or desirable. Should we be prepared for such a scenario, and if so, how could we do that? One possible strategy to tackle this issue is that the technology and its introduction should be *reversible*. The aim of this thesis is to further explore this strategy by answering the following main research question (RQ) and accompanying subquestions (SQ):

RQ: *What are the implications of reversibility for the responsible development and implementation of nuclear energy technologies?*

SQ1: *Under what conditions can nuclear energy technologies be considered reversible?*
SQ2: *Why should nuclear energy technologies be reversible?*
SQ3: *If so, how could the reversibility of nuclear energy technologies be achieved?*

After the introductory chapter 1, the chapters that form the main body of this dissertation each provide a distinct contribution to answering the three subquestions and, by extension, the main research question. Guided by three historical case studies of nuclear energy technology development (i.e., India, France and the USA), chapter 2 answers the first subquestion by formulating the two *conditions under which it can be considered reversible,* i.e., 1) the ability to stop the further development and deployment of a that technology in society, and 2) the ability to undo the undesirable outcomes (material, institutional or symbolic) of the development and deployment of the technology. Chapter 3 subsequently tackles the second subquestion by establishing the *general desirability of technological reversibility* by virtue of its relation to responsibility in Emmanuel Levinas' ethical phenomenology. It argues that technology development is a legitimate response to responsibility but inevitably falls short of the responsibility that inspires it, incessantly calling for technological and political change in the process. Having thus argued that nuclear energy technologies should ideally be reversible, chapters 4 and 5 work towards specific strategies to achieve technological reversibility. Chapter 4 first investigates *the processes that make it difficult to stop the further development and implementation of a nuclear energy technology in society,* thus providing input on how to fulfill the first condition for the reversibility of nuclear energy technologies. To do so, it presents a phenomenological perspective on technology and its adoption based on the work of Alfred Schutz. It also explores different ways in which technology adoption drives the processes of path dependence towards technological lock-in. Chapter 5 examines the history of geological disposal of high-level radioactive waste in the USA. It identifies a number of concrete policy pitfalls that could lead to lock-in and that should consequently be avoided. It also presents a number of general *design strategies that could facilitate the undoing of undesirable consequences* of a technology, thus providing input on how to fulfill the second condition for the reversibility of nuclear energy technologies.

Chapter 6 summarizes the central findings of the thesis and explains how these help to answer the research questions. On top of this, it reflects on a number of complications connected to reversibility considerations. Based on this, it is concluded that the question of irreversibility and reversibility is context- and technology-specific and a matter of degree. The chapter concludes with a reflection on generalizations and limitations of the results. Finally, chapter 7 discusses the implications of this dissertation's results for responsibly experimenting with nuclear energy technologies in society.

Glossary

General	
HLW	High-Level radioactive waste
NEPT	Nuclear energy production technology
NWPA	Nuclear Waste Policy Act
RI	Responsible Innovation
RWM	Radioactive waste management
SNF	Spent Nuclear Fuel
WW2	The Second World War
Institutions	
AEC	Atomic Energy Commission
BARC	Bhabha Atomic Research Centre
CEA	Commissariat à l'Energie Atomique
DAE	Department of Atomic Energy
DOE	Department of Energy
EDF	Électricité de France
ERDA	Energy Research and Development Administration
NEA	OECD Nuclear Energy Agency
NRC	Nuclear Regulatory Commission
Technologies	
FBR	Fast breeder reactor
GD	Geological Disposal
MOX	Mixed oxide fuel
NWTS	National Waste Terminal Storage
PHWR	Pressurized heavy water reactor
PWR	Pressurized water reactor
UNGG	*Uranium naturel graphite gaz* (natural uranium gas graphite reactor)

1 Introduction

The development of nuclear energy technologies[1] in the second half of the 20th century initially came with great hopes of rebuilding nations recovering from the devastation of the Second World War (WW2) or recently released from colonial rule. Despite continuing work on military nuclear applications, taming nuclear fission and putting it to peaceful use constituted a triumph over its hitherto exclusively destructive potential. In countries like France, India, the USA, Canada, Russia, the United Kingdom, etc., nuclear energy became the symbol for development towards a modern and technologically advanced future.

While these lofty aspirations have now lost much of their initial splendor, proponents of nuclear energy still appeal to a number of its other concrete advantages (Teräväinen, Lehtonen, & Martiskainen, 2011). For one, nuclear energy is able to provide reliable base-load power (Brook et al., 2014) from comparatively small amounts of fuel. Moreover, it produces this power with low climate impacts per unit of energy produced, comparable to renewable energy technologies (Lenzen, 2008; Sovacool, 2008). These low climate impacts have led some to propose an important role for nuclear energy in our transition to more sustainable energy systems (e.g., IAEA, 2016). On top of all this, nuclear energy could contribute to some nations' energy independence by increasing domestic energy production and reducing dependence on foreign fossil fuels.

However, nuclear energy does also come with its own particular set of risks, for both current as well as future generations. These risks present a number of ethical concerns, which entail but are not limited to issues of radiological protection (Eggermont & Feltz, 2008; Hansson, 2007a; Shrader-Frechette & Persson, 2002) including environmental and health hazards due to harmful emissions across the nuclear fuel cycle (e.g., Cardis & Richardson, 2000), proliferation of

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1 What does and does not constitute a "nuclear energy technology" is not set in stone, since the definitions, possible degrees and boundaries of what is 'nuclear' are constantly shifting and subject to negotiation (Hecht, 2006, 2007). However, this dissertation focuses on a number of technologies that are so central to nuclear energy infrastructures that their nuclearity is not really in question, i.e., *nuclear power plants, spent fuel and radioactive waste reprocessing plants and high-level radioactive waste disposal facilities*. And while the latter may not be unique to nuclear energy production (e.g., high-level radioactive waste from medical or military applications also needs to be managed through such facilities), they are nevertheless integral to it.

potentially dangerous radioactive materials (Nwosu, 1991; Taebi & Kloosterman, 2008), the intragenerational and intergenerational distribution of risks and benefits in radioactive waste management and disposal (Shrader-Frechette, 2000; Taebi, 2012; Taebi & Kadak, 2010) and safety during power plant operation, the latter having the potential for catastrophic meltdown so graphically illustrated in Chernobyl and Fukushima.

The two undesirable outcomes most symbolic for nuclear energy, i.e., the risk of catastrophe due to reactor meltdown and the risks connected to long-lived radioactive waste, are still fraught with uncertainty[2] despite several decades of nuclear energy production experience (Downer, 2015, 2017, van de Poel, 2011, 2015). First, there is always residual uncertainty concerning the risk of catastrophic meltdown in existing reactors[3], since simulations and lab experiments can never fully account for the context-dependent complexities of real-world implementation (especially for extraordinary circumstances such as earthquakes and/or tsunami's) and empirical statistics on the occurrence and process of meltdowns in power plants are, luckily, rather scarce (van de Poel, 2011). Nevertheless, new reactor types (e.g., Generation III, III+ and IV reactors) are currently being developed and implemented that are, among other things, allegedly able to lower or even eliminate the chance of a core meltdown due to passive or inherently safe design (Taebi & Kloosterman, 2015). Still, even if meltdown is no longer a possibility, uncertainty would persist about the other morally relevant and risky aspects of these new reactor types and the nuclear fuel cycles they require (ibid.). Secondly, there are large uncertainties involved in current approaches to the management and disposal of long-lived radioactive waste (Bredehoeft, 2003; Shrader-Frechette, 1993). Not only are the chemical and physical processes difficult to reliably predict on the immense timescales involved (5000-200.000 years depending on fuel cycle (Taebi & Kloosterman, 2008)), but the way in which future peoples will deal with nuclear waste repositories (if at all) remains difficult, if not impossible, to accurately foresee.

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2 Van de Poel (2011, 2015, 2016) distinguishes between different types of uncertainty, indeterminacy and ignorance. However, for the purposes of this introduction, I collapse that distinction once more under the term 'uncertainty'.

3 Despite the development of increasingly sophisticated methods and models for risk assessment (e.g., U.S. Nuclear Regulatory Commission, 1975), such uncertainty will likely persist due to inherent limitations to predictability (Krohn & Weyer, 1994).

On top of these risks, nuclear energy also tends to import a number of worrisome social and political developments. Most pertinently, nuclear energy technologies are said to invite an authoritarian organization of parts of social and political life (Winner, 1980)[4]. In order to implement and operate them safely and successfully, they tend to invite secrecy, technocratic ideology in decision-making, centralized political authority, and the subordination of challenges to that authority in at least some parts of the institutional landscape (Sovacool & Valentine, 2010; Valentine & Sovacool, 2010; Winner, 1980), often combined with a discourse of national revitalization through indigenous technological progress (e.g., Adler, 1988; Hecht, 1998; Sarkar, 2014). These very characteristics may subsequently hinder democratic governance of these technologies and the consideration of values beyond safety, security and efficiency (see chapter 5). To make matters worse, one can expect these characteristics to play out even more strongly in countries where the division between civil and military nuclear programs and/or fuel cycles is not absolute (compare the nuclear energy programs discussed in chapter 2). In spite of these *general* tendencies, however, the *specific* social and political implications of nuclear energy will differ substantially depending on which nuclear energy technologies are introduced and the social context into which they are introduced (ibid.). As such, it is also difficult to predict exactly what institutional, political and discursive structures would result from the development and implementation of nuclear energy technologies in a given society at a given time. Nevertheless, despite this uncertainty, such 'soft' outcomes (Swierstra & te Molder, 2012) of nuclear energy technologies should surely matter when determining whether nuclear energy technologies are acceptable in a given context.

In all, uncertainties about the risks and socio-political consequences of novel nuclear energy technologies spell trouble for any attempt to determine the desirability of these technologies based on weighing their costs and benefits

4 Winner seems to imply that such authoritarian organization could well permeate all of national politics, creating a 'nuclear state', a popular argument in the 1970's and 1980's. However, experience over the past decades has shown that the fear of such all-encompassing effects was largely overblown (van de Poel, 2015) and that authoritarian organization of social and political life usually has it boundaries institutionally (see chapter 2) and geographically (Felt, forthcoming).

(Kneese, 2006; van de Poel, 2013)[5]. In lieu of the possibility of establishing desirability based on outcomes, however, how does one decide on whether to proceed with new nuclear energy technologies? One approach that explicitly deals with these difficulties conceptualizes *new technologies as social experiments* (van de Poel, 2016). It aims for *continued learning* about risks and other morally relevant outcomes after the implementation of a technology in society, and it diverts attention away from the desirability of the technology itself and more towards the acceptability of the *process by which the technology is developed and implemented.*

1.1. Nuclear Energy as a Social Experiment?

The inability to fully apprehend the outcomes of the development and implementation of new technologies beforehand is not at all unique to nuclear energy[6]. Learning about the side-effects of any sufficiently novel technology before it is actually put into practice is inevitably limited[7]. As such, learning about risks and hazards of new technologies often occurs beyond the boundaries of the laboratory (or field tests): it happens in society. This has led some to argue that society has also become a sort of laboratory, and the introduction of a new technology in society constitutes a social experiment (Felt et al., 2007; Jacobs, Van De Poel & Osseweijer, 2010; Krohn & Weyer, 1994; Levidow & Carr, 2007; van de Poel, 2011, 2013, 2016). As such, in a technologized world like ours, “we are in an unavoidably experimental state” (Felt et al., 2007 p. 68).

However, there are some important differences between laboratory and social experiments with new technologies (van de Poel, 2011). First, since social

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5 Next to such practical difficulties, there are also principled reasons why cost-benefit analysis is a problematic method for determining the desirability of projects. Of these, problems of prediction and control over future actions are especially applicable to the case of nuclear energy (Hansson, 2007b).

6 However, the fact that nuclear energy technologies usually involve complex infrastructures does exacerbate the problem of prediction (Downer, 2017; Krohn & Weyer, 1994)

7 This limitation has practical reasons (e.g., limited budgets and time, insufficient quality of data, etc.), but also principled ones. Learning about the risks of a new technology in the lab is necessarily limited because it cannot sufficiently take into account long-term cumulative and interaction effects and recursive non-linear systems dynamics, laboratory and field tests are often not representative of actual technological practice, and some risks are simply not foreseen due to ignorance of their existence (Krohn & Weyer, 1994; van de Poel, 2011).

experiments are not always recognized as such, monitoring and data gathering is often less organized or in some cases even absent. Secondly, social experiments are less controllable, in no small part due to their societal embedding and lack of clear experimental boundaries. For example, the global fallout of the Chernobyl and Fukushima nuclear disasters should attest to the difficulty of containing the effects of experiments gone awry. Last but not least, since social experiments take place beyond the laboratory, they involve many more and different people than standard experiments do. Indeed, experiments with nuclear energy technologies can involve whole societies through their political consequences (see chapter 2) and experimenting with high-level waste management technologies involves members of hundreds if not thousands of future generations. At the same time, social experiments with new technologies are routinely "deleted from public view and public negotiation. [Yet, if] citizens are routinely being enrolled without negotiation as experimental subjects, in experiments which are not called by name, then some serious ethical and social issues would have to be addressed" (Felt et al., 2007 p. 68).

Indeed, while conscious learning through deliberate social experimentation with new technologies has the potential to overcome uncertainty and ignorance of risks and hazards, it also implies that one is experimenting with human subjects. As such, analogous to the way standard experiments with human subjects are subject to rather stringent ethics considerations based on principles like non-maleficence, beneficence, respect for autonomy, and justice (Beauchamp & Childress 2013), experimenting with new technologies in society has a number of important normative implications for the way in which such social experiments are to be organized. Concretely, van de Poel (2011, 2013, 2016) has suggested a set of conditions for responsible experimentation with new technologies in society (see table 1.1), which experiments with nuclear energy technologies would also have to fulfil if they are to be responsible.

Table 1.1 An ethical framework for experimental technology (van de Poel, 2016)

1	Absence of other reasonable means for gaining knowledge about risks and benefits
2	Monitoring of data and risks while addressing privacy concerns
3	Possibility and willingness to adapt or stop the experiment
4	Containment of risks as far as reasonably possible
5	Consciously scaling up to avoid large-scale harm and to improve learning

6	Flexible set-up of the experiment and avoidance of lock-in of the technology
7	Avoid experiments that undermine resilience
8	Reasonable to expect social benefits from the experiment
9	Clear distribution of responsibilities for setting up, carrying out, monitoring, evaluating, adapting, and stopping of the experiment
10	Experimental subjects are informed
11	The experiment is approved by democratically legitimized bodies
12	Experimental subjects can influence the setting up, carrying out, monitoring, evaluating, adapting, and stopping of the experiment
13	Experimental subjects can withdraw from the experiment
14	Vulnerable experimental subjects are either not subject to the experiment or are additionally protected or particularly profit from the experimental technology (or a combination)
15	A fair distribution of potential hazards and benefit
16	Reversibility of harm or, if impossible, compensation of harm

However, it may be argued that nuclear energy is no longer experimental since there is over six decades of experience with nuclear energy production. Still, there are both epistemic as well as moral reasons to think that the experimental framework can be meaningfully applied to nuclear energy technologies (van de Poel, 2015).

The first epistemic reason lies in the fact that uncertainty is still very much an issue with nuclear energy technologies, thus making at least some of them *de facto* experimental. For one, a number of nuclear energy technologies are still being developed or have not yet been widely implemented, technologies with which operating experience is accordingly lacking and uncertainty about their real-world impacts is thus significant. As such, these technologies can be reasonably considered experimental. For example, novel nuclear reactor designs (Generation III, III+ and IV) import new uncertainties, as does the geological disposal of long-lived radioactive waste[8]. However, even technologies with which

8 Despite the fact that we have decades of experience with geological disposal, that experience only covers a fraction of the time a waste repository is supposed to contain harmful radionuclides (van de Poel, 2015), with containment after repository closure being more difficult to guarantee far into the future (Barthe, 2010; Shrader-Frechette, 1993) due to practical and

there is already considerable experience may encounter novel uncertainties when implemented into a new geographical, institutional or cultural context or simply when their current context changes considerably (e.g., in the 1970's in the USA. See chapter 2). This could alter the potential impacts of the technology or invite adjustments to the technology itself, resulting in new uncertainties. As such, 'old' nuclear energy technologies can also be considered experimental, at least to the extent that their context is new or in flux. The second epistemic reason for considering nuclear energy technologies as experimental is that doing so allows for *deliberate* experimentation with them. Experimenting deliberately increases the possibility to learn from an experiment with nuclear energy technologies. This would not only help to overcome uncertainty about their impacts as discussed above (impact learning) but supports learning about the proper institutions for embedding such technologies in society (institutional learning) and about the relevant values, norms and moral issues (normative learning)(van de Poel, 2015 p. 190).

On top of these epistemic reasons, there are a number of moral reasons for considering nuclear energy technologies as experimental. First, it would recognize uncertainty as an important factor in the moral debate, especially those uncertainties that cannot be clearly expressed in terms of risks. Secondly, considering nuclear energy technologies as experimental shifts the focus of the debate away from the inherent acceptability of the technology itself and towards the conditions (if any) under which an experiment with these technologies in society would be acceptable. This could soften the current stalemate between nuclear opponents and proponents. Third, recognizing nuclear energy technologies as experimental can help to develop a moral framework to perform such experiments responsibly and revise it based on deliberate normative learning.
Based on these reasons, we can consider at least some contemporary nuclear energy technologies as social experiments[9]. However, as explained above, this insight comes with important normative implications. One of these implications is that for such an experiment with a nuclear energy technology in society, we have to be prepared for learning that the experiment has gone wrong.

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inherent limits to predictability, including the possibility of future human intrusion (Krohn & Weyer, 1994; van de Poel, 2011).

9 This is not to say that past nuclear energy technologies were not experimental. Rather, they were only *de facto* experimental, whereas contemporary technologies can be made deliberately experimental.

1.1.1. Experiments gone wrong and the need for reversible technologies

Among van de Poel's conditions for morally responsible social experimentation (see table 1.1), there are some that are meant to be able to deal with experiments that have gone wrong[10]. That is, they are meant to prepare an experimenter for learning what she would rather not: that it is no longer responsible or desirable to continue the experiment, or at least certain aspects thereof. These conditions are of two kinds. On the one hand, some are meant to deal with the *undesirable outcomes* of the experiment: a) the containment of risks as far as reasonably possible and b) the reversibility of harm or, if impossible, compensation of harm. The others are concerned with the possibility of making *necessary adjustments* to the experiment. These are c) the flexible set-up of the experiment and the avoidance of lock-in of the technology and even d) the possibility and willingness to stop the experiment. What binds these conditions is the focus on 'undoing what has been done', reversing previous decisions and outcomes of the social experiment. In turn, it stands to reason that ensuring the reversibility of the experiment requires the *reversibility of the technology* being experimented with.

However, how would one go about making nuclear energy technologies reversible? For example, does the issue of long-lived radioactive waste not already prove problematic for such an approach? Obviously, such questions are hard to answer without a good understanding of what it actually means for a nuclear energy technology to be reversible in the first place. In the following sections, the use of reversibility and other concepts similar to it in nuclear energy are briefly discussed. As this discussion shows, notions like reversibility are not new to the nuclear energy debate. In spite of this, the current literature does not provide a conceptualization of reversibility that is sufficiently encompassing to cover the relevant conditions for responsible experimentation with nuclear energy technologies in society.

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10 The going 'wrong' of such an experiment is to be read in light of the initial hopes the technology was meant to realize. Of course, discovering previously unknown hazards that disqualify a technology is likely a sign of a successful social experiment in its own right.

1.2. Current Approaches to the (Ir)reversibility of Nuclear Energy Technologies[11]

The notion of reversibility (or in its opposite form: irreversibility) is not new to discussions of nuclear energy and its hazardous byproducts (see section 5.2 for an overview). In such discussions, it is most often encountered in descriptions of physical processes. That is, it is generally used to describe (ir)reversible mechanical/chemical/thermo-dynamic processes in nuclear energy production or radioactive waste management. For example, there is a lot of attention for irreversible flows and migrations of radioactive isotopes in technical, environmental or geological systems, which is relevant for the storage and disposal of radioactive waste. On top of this, one finds it used to distinguish some consequences based on their irreversible nature, e.g., irradiation causing mutations and other cell damage, or damage to the environment and its ecosystems. Some have also categorized long-lived radioactive waste as essentially irreversible.

Such uses of the notion of reversibility help us to understand the physical processes involved in nuclear energy production and are indispensable for successfully developing and implementing nuclear energy technologies as well as monitoring and managing their effects. Nevertheless, since they only describe physical processes, they do not provide much guidance for setting up responsible experiments with nuclear energy technologies in society. Indeed, at first glance, no notion of reversibility seems to be available in the literature on nuclear energy that is also sufficiently encompassing and technology-oriented to inform such responsible experimentation. However, inspiration for the development of such a notion of reversibility can still be drawn from a) literature on radioactive waste management policy and b) concepts from the economic and innovation studies literature such as a technology's inflexibility (Collingridge, 1980, 1983; Genus, 1995) or path dependence and lock-in (Arthur, 1990; Cowan, 1990; David, 2007). Both are briefly discussed below.

11 Parts of this section (especially 1.2.1) are based on section 5.2 of this dissertation, which investigates the use of the notion of reversibility in nuclear energy.

1.2.1. Undoing what has been done: reversibility in radioactive waste management policy

The development and implementation of geological repositories for high-level radioactive waste (HLW) and spent nuclear fuel (SNF)[12] have not generally exhibited the same momentum as some other nuclear energy technologies have in the past, in spite of increasing global stockpiles of HLW and SNF (IAEA, 2008) and a general agreement that geological disposal is the most appropriate strategy for dealing with these byproducts of nuclear energy production (OECD Nuclear Energy Agency, 1995; U.K. Nuclear Decommissioning Authority, 2008, 2013).

To remediate this problem, the past decades have seen an increasing interest in two reversibility-related considerations in radioactive waste management policy generally and the geological disposal of HLW and SNF in particular (Cézanne-Bert & Chateauraynaud, 2010; OECD Nuclear Energy Agency, 2012). First, *reversibility* refers to the possibility in principle to change or reverse decisions made during the implementation process of a waste storage or geological disposal facility. Secondly, *retrievability* refers to the possibility in principle to retrieve radioactive waste from a waste storage or geological disposal facility. The combination of reversibility and retrievability is supposed to increase intergenerational equity by keeping options open for future generations, facilitate remedial action in case of lower-than-expected repository performance, and increase social acceptance of waste disposal facilities (OECD Nuclear Energy Agency, 2011).

For the purpose of responsible social experimentation with nuclear energy technologies (or technologies more generally), however, these considerations are too narrowly defined[13]. For one, while retrievability is a legitimate strategy for dealing with possible undesirable consequences of geological disposal, it is also decidedly technology-specific and thus less applicable to other nuclear energy technologies such as power plants or reprocessing facilities. In turn, reversibility as understood in the context of radioactive waste disposal is restricted to reversing decisions *within* the confines of the implementation of a specific waste disposal facility. The question of whether to (continue to) implement that facility

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12 See section 5.2.

13 Of course, this is not surprising given that they were never actually meant to serve that purpose.

or, more importantly, whether we should stop experimenting with this technology entirely does not fall under the rubric of this notion of reversibility. If it is to be appropriate for responsible social experimentation, however, these questions should be included in reversibility considerations.

In the next section, I introduce two concepts that are central to understanding this difficulty of adjusting or stopping further implementation of nuclear energy technologies: inflexibility and path dependence.

1.2.2. Increasingly irreversible: the path towards inflexibility and lock-in

Technologies have a tendency to become less susceptible to deliberate human control the more they become enmeshed in the social and technological fabric of daily life. That is, when technologies are new, they are more open to change based on deliberate human intervention. As time goes by and they get more integrated into larger systems, technologies come to exhibit a more deterministic character. Such "technological momentum" (Hughes, 1969, 1994) has probably been presented most emblematically in the form of the Collingridge dilemma, also known as the 'dilemma of control' (Collingridge, 1980). The dilemma of control posits this tendency of technology in terms of a discrepancy between knowledge and power. That is, in the early stages of a technology's development and/or implementation, the power to make changes is at its greatest, but information about the impacts of the technology is lacking. By the time this information becomes available, changing or controlling the technology has become difficult. In other words, the technology has become *inflexible* (Collingridge, 1980; Genus, 1995).

However, not all technologies are equally inclined to become inflexible. A number of factors increase the chance and extent to which technologies become inflexible. Some of these factors are technology-related, namely a dependence on extensive and complex infrastructures, long lead time, massive unit size and high capital intensity. Since nuclear energy technologies generally exhibit these characteristics, they have a large tendency to become inflexible (Collingridge, 1983). Other factors that contribute to inflexibility are more social in nature, such as centralized decision-making, a widely shared technical mission, an organizational concentration of expertise, which could together lead to the formation of strong coalitions in favor of the status quo (Collingridge & James, 1991). Most if not all of these social factors also apply to nuclear energy technologies[14]. Therefore, nuclear energy technologies can be said to have a *strong propensity for inflexibility*.

However, for a technology to reach the point of inflexibility, actors have to commit to it and it has to go through an extended process of development and implementation (as per the dynamic of technological momentum or the dilemma of control). Such a process of repeated technology adoption[15] can under certain conditions lead to inflexible technologies even if the technology does not have a strong tendency for inflexibility. According to the theory of *path dependence*[16], once a specific technology gains a small but significant lead over alternatives, this technological 'path' gets reinforced if the adoption of the technology exhibits positive feedback (Arthur, 1989, 1994; David, 1985), i.e., when adopting the dominant technology makes it comparatively more (or alternatives technologies less) attractive to future adopters (David, 2007; Page, 2006; Vergne & Durand, 2011). Through positive feedback mechanisms such as increasing returns to scale, network economies or learning effects, increasing adoption can then lead to an inflexible outcome: the technology becomes locked-in (Arthur, 1994). Such positive feedback mechanisms have been shown to contribute to the lock-in or inflexibility of nuclear energy technologies (Bergen, 2016a, 2016b; Cowan, 1990).

The implications of inflexibility and path dependence for nuclear energy technologies indicate that responsible experimentation with such technologies would not be easy. Specifically, they give reason to suspect that stopping the experiment or even changing the experimental set-up will be especially difficult for these technologies, and increasingly so as the experiment continues. However, understanding how and why nuclear energy technologies fall prey to inflexibility and lock-in may nevertheless help to avoid such difficulties.

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14 For the applicability of the technical and economic factors to nuclear energy technologies, see (Collingridge, 1983). For the applicability of the social factors, see chapters 2 and 5 of this dissertation.

15 See chapter 4 for an exploration of how these steps involve repeated adoption of the technology.

16 For a more elaborate discussion of the theory of path dependence, see chapters 4 and 5.

1.3. Objectives and Research Questions

This dissertation's point of departure lies in two of the themes identified above. First, given the nature and extent of the risks connected to nuclear energy, it recognizes the potential of the notion of social experiments for the responsible development and implementation of nuclear energy technologies. This shifts the focus away from the question of the desirability of nuclear energy technologies themselves and towards the conditions under which *experiments* with these technologies are acceptable (van de Poel, 2013, 2015). Secondly, it acknowledges that some of the conditions for experimenting responsibly with nuclear energy technologies in society might be particularly difficult to fulfill. Specifically, it targets those conditions related to reversibility, i.e., the possibility of adjusting or even stopping the experiment (due to a propensity for inflexibility and lock-in) and the containment of risks and reversibility of harm (due to the longevity of some radioactive waste products).

In light of these observations, a better understanding of the reversibility of nuclear energy technologies should increase our ability to experiment responsibly with them. Likewise, it might improve the public debate on the acceptability of such experiments by providing useful conceptual resources to discuss reversibility-related conditions. As such, the main goal of this dissertation is to explore the implications of the concept of reversibility for responsibly experimenting with nuclear energy technologies in society. To do so, it seeks to answer the following main research question (RQ) and accompanying subquestions (SQ):

RQ: *What are the implications of reversibility for the responsible development and implementation of nuclear energy technologies?*

SQ1: *Under what conditions can nuclear energy technologies be considered reversible?*
SQ2: *Why should nuclear energy technologies be reversible?*
SQ3: *If so, how could the reversibility of nuclear energy technologies be achieved?*

Answering the three subquestions is vital to understanding the implications of reversibility for the responsible development and implementation[17] of nuclear

[17] While the distinction between development and implementation is made to highlight the importance of both phases for reversibility considerations, it does not necessarily hold so

energy technologies. The first subquestion asks under what conditions nuclear energy technologies can be considered reversible. In so doing, it calls for the development of a novel notion of technological reversibility that is also appropriate for social experimentation with nuclear energy technologies in society. This dissertation develops such a notion in the form of *conditions for technological reversibility* against which technology development, policy and practice can actually be assessed. Doing so should promote compatibility with the practice-oriented conditions for responsible experimentation found in table 1.1, while also facilitating the articulation of specific strategies to make nuclear energy technologies more reversible. In chapter 2, two such conditions for technological reversibility are proposed, supported by historical case studies of early nuclear energy development in India, France and the USA. These cases are studied through the lens of a new conceptualization of technology development that is receptive to the technological and social factors contributing to inflexibility as well as to the positive feedback dynamics behind path dependence.

Once the conditions for technological reversibility are clear, further inquiry is possible into the implications of reversibility for responsibly experimenting with nuclear energy technologies in society. These implications are in turn determined by two factors: its desirability on the one hand, and its feasibility on the other. The desirability and feasibility of reversibility of nuclear energy technologies are represented in the second and third subquestions respectively.

The second subquestion asks *why* nuclear energy technologies should be reversible. This dissertation took its *prima facie* interest in reversibility because its desirability is implied by the conditions for responsible experimentation in table 1.1. However, these conditions are themselves subject to change based on what is learned in these experiments (van de Poel, 2016). As such, chapter 3 aims to provide normative support for the desirability of technological reversibility that is independent of (yet compatible with) the social experimentation framework. To do so, it develops a Levinasian conceptualization of technology, innovation and its relation to responsibility. The resulting framework helps to explain why technologies (and, by extension, nuclear energy technologies) should indeed be reversible, at least to a degree.

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strictly in actual practice. Especially for complex and interdependent technologies, development and implementation might significantly overlap.

The third subquestion looks into the feasibility of reversible nuclear energy technologies by asking how such reversibility could actually be achieved. Answering this question means outlining how to fulfill the conditions for technological reversibility that were formulated in response to the first subquestion. Given nuclear energy's propensity for inflexibility, chapters 2, 4 and 5 investigate the socio-technical dynamics that make it *difficult* to fulfil the first condition for technological reversibility. They do so by adapting and applying existing theory on the structuration of technology (chapter 2) and path dependence and lock-in (chapters 4 and 5). Based on these insights, a number of strategies can be formulated for *avoiding* irreversibility. Chapter 5 studies the case of geological disposal of high-level radioactive waste in the USA and shows how the technology became locked-in. In addition, it proposes a number of strategies for undoing GD's undesirable consequences. These can be used as heuristics for assessing the extent to which the second condition has been fulfilled and as design strategies for maximizing its potential.

1.4. Overview of Chapters

The four chapters that form the body of this thesis were originally devised for publication in peer-reviewed journals. Their abstracts are presented below and serve as short summaries for the different chapters. Chapters 2, 3 and 5 have already been published. Citations are provided in the corresponding footnotes.

Chapter 2: Reversibility and Nuclear Energy Production Technologies: A Framework and Three Cases[18]

Recent events have put the acceptability of the risks of nuclear energy production technologies (NEPT) under the spotlight. A focus on risks, however, could lead to the neglect of other aspects of NEPT, such as their irreversibility. I argue that awareness of the socio-historical development of NEPT is helpful for understanding their irreversibility. To this end, I conceptualize NEPT development as a process of structuration in which material, institutional and discursive elements are produced and/or reproduced by purposive social actors. This conceptualization is used to structure an analysis of how irreversibility arose in

[18] This chapter has been published as Bergen, J. P. (2016) 'Reversibility and Nuclear Energy Production Technologies: A Framework and Three Cases', in *Ethics, Policy & Environment* 19 (1): 37–59.

the first decades of NEPT development in India, France and the USA, and how some NEPT have been reversed or partially reversed. Lastly, two general conditions for reversible NEPT are formulated based on this analysis.

Chapter 3: Responsible Innovation in Light of Levinas: Rethinking the Relation between Responsibility and Innovation[19]

To date, much of the work on Responsible Innovation (RI) has focused on the 'responsible' part of RI. This has left the 'innovation' part in need of conceptual innovation of its own. If such conceptual innovation is to contribute to a coherent conception of RI, however, it is crucial to better understand the *relation* between responsibility and innovation first. This paper elucidates this relation by locating responsibility and innovation within Emmanuel Levinas' phenomenology. It structures his work into three 'stages', each described in terms of their leading experience and objectivation regime. This analysis identifies a need for constant innovation of political and technological systems, originating from and motivated by our responsibility to others. It also shows the relation between responsibility and innovation to be threefold: foundational, ethical, and structural. These insights could help RI to avoid some pitfalls of 'regular' innovation, and provide moral grounding for important aspects of RI.

Chapter 4: Path Dependence, Agency and the Phenomenology of Technology Adoption

The theory of path dependence remains a popular explanation for why markets or societies become locked into specific technological trajectories that become increasingly inflexible over time. However, a number of scholars have become skeptical of the value of historical case studies for studying path dependence (the dominant method up to this point) and instead recommend other approaches like lab experiments and simulations. Nonetheless, the 'thick' description of actual cases may still have significant value for the study of technological path dependence. First, thick socio-technical descriptions of the environment in which technology adoption occurs reveals normatively problematic aspects of path dependence beyond inefficiency. Secondly, a thicker, structurational notion of agency in path dependent processes could help to alleviate concerns about

19 This chapter has been published as Bergen, J. P. (2017) 'Responsible Innovation in light of Levinas: rethinking the relation between responsibility and innovation', in *Journal of Responsible Innovation*. Available online at: http://www.tandfonline.com/doi/full/10.1080/23299460.2017.1387510

path dependence' allegedly excessive determinism and its reliance on contingency for path creation. This paper aims to contribute to such a structurational notion of agency by developing conceptual resources for agent-centered descriptions of technological path dependence. It does so by reinterpreting the basic evolutionary building blocks of path dependence (i.e., technology adoption, technology and the social selection environment) through the lens of Alfred Schutz' social phenomenology. The resulting perspectives provide a number of conceptual resources that should allow for better describing why and how agents make the technology adoption decisions that they do, and the way in which technology and the social selection environment mediate those choices and their consequences.

Chapter 5: Reversible Experiments: Putting Geological Disposal to the Test[20]
Conceiving of nuclear energy as a social experiment gives rise to the question of what to do when the experiment is no longer responsible or desirable. To be able to appropriately respond to such a situation, the nuclear energy technology in question should be *reversible*, i.e. it must be possible to stop its further development and implementation in society, and it must be possible to undo its undesirable consequences. This paper explores these two conditions by applying them to geological disposal of high-level radioactive waste (GD). Despite the fact that considerations of reversibility and retrievability have received increased attention in GD, the analysis in this paper concludes that GD cannot be considered reversible. Firstly, it would be difficult to stop its further development and implementation, since its historical development has led to a point where GD is significantly locked-in. Secondly, the strategy it employs for undoing undesirable consequences is less-than-ideal: it relies on containment of severely radiotoxic waste rather than attempting to eliminate this waste or its radioactivity. And while it may currently be technologically impossible to turn high-level waste into benign substances, GD's containment strategy makes it difficult to eliminate this waste's radioactivity when the possibility would arise. In all, GD should be critically reconsidered if the inclusion of reversibility considerations in radioactive waste management has indeed become as important as is sometimes claimed.

[20] This chapter has been published as Bergen, J. P. (2016) 'Reversible Experiments: Putting Geological Disposal to the Test', in *Science and Engineering Ethics* 22 (3): 707–733.

2 Reversibility and Nuclear Energy Production Technologies: a Framework and Three Cases

Recent events have put the acceptability of the risks of nuclear energy production technologies (NEPT) under the spotlight. A focus on risks, however, could lead to the neglect of other aspects of NEPT, such as their irreversibility. I argue that awareness of the socio-historical development of NEPT is helpful for understanding their irreversibility. To this end, I conceptualize NEPT development as a process of structuration in which material, institutional and discursive elements are produced and/or reproduced by purposive social actors. This conceptualization is used to structure an analysis of how irreversibility arose in the first decades of NEPT development in India, France and the USA, and how some NEPT have been reversed or partially reversed. Lastly, two general conditions for reversible NEPT are formulated based on this analysis.

2.1. Introduction

The nuclear disaster in Fukushima is still vivid in our collective memory. The subsequent uproar and far-reaching policy debates (e.g. in Germany) have put nuclear energy back on the agenda and under critical examination. One of the central questions is, of course: should the development and implementation of nuclear energy production technologies (NEPT) be continued and, if so, in what way? In considering this question, the nature and acceptability of the risks and benefits of NEPT have received much attention (e.g. Hale, 2011; Parkins & Haluza-Delay, 2011; Roeser, 2011; van de Poel, 2011). However, a focus on risks can result in failing to appreciate other aspects of NEPT that are relevant to the question whether to continue them, and requires comprehension of the socio-historical process of NEPT development. This paper contributes insights into a specific feature that arises as NEPT are developed, namely technological irreversibility. Irreversibility has received attention in the literature on nuclear power and emerging technologies (e.g. Cowan, 1990; van Merkerk & van Lente, 2005) and has been implicitly present in some of the socio-technical literature, for example in social embeddedness (Granovetter, 1985), entrenchment (e.g. Koch & Stemerding, 1994; Mulder & Knot, 2001), and path dependence and lock-in (e.g. Arthur, 1989, 1994; David, 2007; Liebowitz & Margolis, 1995). The issue of irreversibility is of great importance for whether to continue developing or using NEPT. There are a number of reasons for this. Firstly, NEPT are characterized by a degree of residual uncertainty and ignorance concerning risks, even after risk analysis has been performed and implementation in society has already begun (van de Poel, 2011). However, as learning about the technology continues, possibilities for making changes to the technology generally decrease.[21] With this in mind, Collingridge (1980, 1983) argued that keeping NEPT flexible is paramount to optimal outcomes from its development.[22] Secondly, better technological solutions for achieving the same goals as NEPT might be found. Replacing NEPT with another technology requires some degree of reversibility. Finally, even democratic considerations could drive one to reverse NEPT development.

However, before it is possible to actually incorporate technological reversibility/ irreversibility as a useful variable in considering the acceptability of NEPT, it must first be properly identified and analysed. And while the above-mentioned frameworks and concepts could be helpful in this regard, they generally leave black-boxed the question what technology is, and uphold a distinction between agency and technology that arguably does not do justice to their co-constitutive relation (e.g. Orlikowski, 1992, 2007). This paper provides a framework that incorporates these points by characterizing NEPT development as a process of structuration. Building on some of the basic tenets of structuration theory (Giddens, 1984), augmented with insights from the sociology of expectations (e.g. Borup, Brown, Konrad & van Lente, 2006), this paper presents technology as a structural property of social systems. This is further elaborated upon in sections 2.2 and 2.3. In sections 2.4, 2.5 and 2.6, the first decades of the NEPT development in India, France and the USA are analysed. Finally, what insight this analysis provides into the reversibility and irreversibility of NEPT is explained in section 2.7.

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21 This is part of the famous Collingridge Dilemma, or the dilemma of control (Collingridge, 1980).

22 Admittedly, Collingridge's notion of flexibility is less severe in its outlook than reversibility as such. It is, however, to a certain extent comparable in what I mean by 'partial reversibility' below.

2.2. Technology Development as a Process of Structuration

Reflection on technology often focuses on material artefacts and 'hard' aspects such as risks and benefits (Sørensen, 2004; Swierstra & te Molder, 2012). In what follows, a different conceptualization of technology is introduced in order to further our understanding of technological irreversibility. This conceptualization is essentially a social one, since technology development is not detachable from its social context and is wrought with subjectivity and contingency (Pinch & Bijker, 1987). Additionally, technology is developed by people with certain goals in mind. These goals are neither pre-given nor random; they are based in socially constructed, subjective human aspirations. Aspirations entail hopes and ambitions, held by individual human agents. They are the discursive[23] result of an agent's reflexive monitoring of its actions and inner motivations as well as its social and physical surroundings. These aspirations can be shared between agents and then function as expectations[24] that determine the direction of technology development by mobilizing actors and resources and by setting a development path through promising and visioning (Borup et al., 2006). And while these aspirations guide the direction of technology development, technology in turn influences our aspirations.

The theory underlying this idea – the theory of structuration – was first proposed by Anthony Giddens (1979, 1984). It builds on what Giddens calls the 'duality of structure', meaning that 'the structural properties of social systems are both the medium and the outcome of practices that constitute these systems' (Giddens, 1979, p. 69), wherein the continuous reciprocal reproduction of structure and agency is what he calls the 'structuration process'. The structural properties of social systems are 'institutionalized features of social systems, stretching across time and space' (Giddens, 1984 p. 185). Orlikowski (1992) suggests that technology is a prime example of such a structural property.[25] Based on Giddens' 'duality of structure', Orlikowski proposes a recursive notion

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23 That is, they can be uttered in language. As such, they are operationalizable as guides for action, and can be shared with other agents.

24 Such expectations and their effect on technological development are the subject of the 'sociology of expectations' (see Brown & Michael, 2003).

25 This is arguably more in line with the 'duality of structure' than Giddens' own idea of technology, which did not extend much beyond a 'means of material production/reproduction', or resources implicated by actors in structures of domination (Giddens, 1984 p. 258).

of technology in the form of the ‘duality of technology’ (p. 405). Material technology is created through action and enables humans to do things that were previously not possible. On the other hand, it constrains human agents by making certain options for action more or less attractive or affordable.[26] By habitually calling these technologies into play, actors objectify and institutionalize them (Orlikowski, 1992). This is crucial, since the stability implied allows actors to make sense of technologies and discover how to use them, and are thereby able to take advantage of technologies to do 'work'.

What sorts of structural elements give rise to technology as a structural property of social systems through reproduction and transformation by agents? Arts, Leroy and Tatenhove (2006, p. 99) present a framework for the analysis of policy domains that is based on the duality of structure. It identifies four dimensions: actors, discourses, rules of the game and resources. In light of Orlikowski’s ‘duality of technology’, I have revised this division resulting in a different topography of the structural elements implicated in a duality of technology, as shown in table 2.1.

26 Be it by having limited functionalities (e.g. nuclear reactors producing weapon-grade plutonium or not), by having negative outcomes other than intended functionality (e.g. producing hazardous wastes in the process of producing electricity) or by seemingly necessitating certain institutional arrangements (e.g. NEPT requiring a strong authoritative state as argued by Winner (1980)).

Table 2.1 Structural elements implicated in the duality of technology

Structural dimension	Discursive	Institutional	Material
Space for action constituted and constrained by	Discourse	Rules	Material affordance
Resources drawn upon	Discursive resources	Authoritative resources	Allocative resources
Technology-specific	Shared aspirations, specific content of documents, and identification/ symbolic features of a technology…	Solid work routines, codes, procedures for decision-making, organizations responsible for the technology's working…	Material resources, means of material production and reproduction, produced goods…
General	Larger symbolic orders	Larger institutional features, such as the State, market, etc.	Material features of the environment, including other technologies

In the discursive dimension, I distinguish between a) discourse as agents' shared views and narratives as enabling and constraining agency, and b) discursive resources drawn upon in developing technology (including shared aspirations). The institutional dimension of technology includes rules and authoritative resources, namely the elements implicated in the regulation and coordination of human action. The material dimension of technology includes allocative resources, as well as a technology's material affordance, namely the idea that the specific material structure of a technology makes certain actions more or less affordable than others. As such, material elements are made functionally analogous to discursive or institutional ones, and the three dimensions can be taken up in parallel for an analysis of technological irreversibility. Lastly, while actors are always implicated in the reproduction and transformation of NEPT, an analysis of the elements that make up NEPT focuses on structure rather than agency. As such, actors and their actions and interactions are treated here as a necessary background condition for the historical analysis of the production, reproduction and transformation of the elements of NEPT.

In sum, a technology consists of relatively stable sets of elements of all three structural dimensions, stretching across time and space through recursive implication by social actors, delineated from the rest of the social system by their discursive identification as belonging to a specific technology.

2.3. Structuration and Technological Irreversibility

The continual reproduction and transformation of social structure through action gives rise to the longevity of institutions. Indeed, the structural properties of social systems (like technology) can exhibit amazing tenacity due to the structuration process involved exhibiting positive feedback, or as Giddens calls this phenomenon, 'circuits of reproduction' (Giddens, 1984 p. 190). When this dynamic is sufficiently strong, technology development can 'get caught' in circuits of reproduction and a technology becomes more and more irreversible. That is, stopping its development or undoing its constitutive structural elements (see table 2.1) becomes increasingly difficult. My conception of such a circuit of technology reproduction is shown in Figure 2.1.

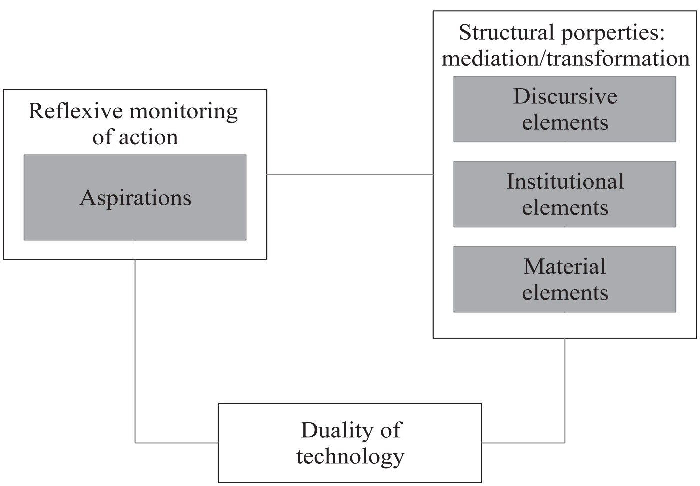

Figure 2.1 Circuit of technology reproduction

According to Giddens, one important aspect contributing to the continuation of circuits of reproduction is the absence of contradiction, or as I call it here, the absence of disalignment. When it is difficult or practically impossible for agents to reproduce a set of elements because acting upon one element would weaken the other(s), there is disalignment between these elements. As I will show in the cases below, it is often disalignment between structural elements[27] that incite conflict and offer opportunities for disruptive interventions in the development of NEPT, possibly reversing the technology or elements thereof. However, not all disalignment leads to disruptive events. One reason for this is that the introduction of new elements (e.g. renewable energy sources, innovative legislation or a redefinition of sustainability) is difficult, because it is also likely to be disaligned with a system structured 'around' the old technology. Another important reason for this phenomenon is the asymmetrical distribution of resources in favour of those supporting the status quo, which allows them to prevent others from acting upon disalignments (e.g. by secrecy or sanctions) or to limit the effectiveness of counter-efforts (e.g. by being in powerful networks with significant decision-making power). In the end, the consequences of disruptive events might be limited to undoing only some elements of a technology, and leaving the majority of elements in place. In this case, one might speak of the partial reversal of that technology.

In what follows, this conceptualization of technology and its development is applied to explore the development of NEPT in India, France and the USA in the period between 1945 and 1980. These specific countries were selected because a) they have all developed domestic NEPT, which is interesting for a framework conceptualizing technology development; b) they started doing so at more or less the same time, which makes the global background conditions similar; and c) their specific socioeconomic, cultural and political backgrounds differ considerably, which provides some interesting divergences in technology development trajectories[28]. In this analysis, a combination of material, institutional and

27 Note that Giddens (1984) is principally interested in contradiction at a much more fundamental level (p. 198).

28 One might expect here, rather than India, France and the USA, countries in which nuclear energy has been successfully abandoned like Italy or Germany. However, given the extraordinary and traumatic nature of the events that eventually triggered this abandonment (the Chernobyl and Fukushima disasters respectively), it seems that it is basically the *difficulty* of abandoning NEPT (i.e. irreversibility) that must first be understood in order to then understand how it can be overcome. Moreover, neither Italy nor Germany have really indigenously developed NEPT and as such, could not adequately showcase the theory presented in this paper of how irreversibility arises during technology development. I suspect, however, that applying the theory of technological irreversibility (sections 2.2 and 2.3) and the conditions for reversible technology (section 2.7.4) developed in this paper to these cases could shed light on why these countries were successful in abandoning NEPT as well as on the extent to which the indigenousness of a technology contributes to its irreversibility.

discursive elements of NEPT are brought together with the socio-historical context in which they arose. As such, the analysis consists of building a socio-historical narrative for each country's NEPT development trajectory, structured according to the three structural dimensions, and a discussion of the main elements involved in the circuits of NEPT reproduction and their disturbance, if applicable.

2.4. India

The birth of the Indian nuclear energy programme can be traced back to the years after the country gained independence from British rule in 1947. Under Nehru (India's first prime minister), development and independence became themes that guided both state policy and popular sentiment. One important part of development policy was a domestic nuclear energy programme. The government began by setting up the Tata Institute for Fundamental Research in 1948. Its director, Homi Bhabha, can be called the father of the Indian nuclear energy programme, since his three-phase plan guides NEPT development to this day. In 1954, the programme gained pace and importance with the creation of the Department of Atomic Energy (DAE) and by 1956, the first test reactor was running. In 1957, what would become the Bhabha Atomic Research Centre (BARC) was set up and by 1969, India's first commercial reactors were online.

Nuclear energy development continues to this day (although nuclear energy provides only about 4% of India's electricity) and is expanding rapidly as the programme enters the second of its three planned phases. The first phase consisted of pressurized heavy water reactors (PHWRs) to generate energy and the necessary plutonium fuel for the second phase, in which fast breeder reactors (FBRs) will burn this fuel, thus generating the plutonium and uranium isotopes necessary for a thorium-based[29] reactor fleet by 2050 (phase three), by which time 25% of India's electricity needs should be met by nuclear fission (World Nuclear Association, 2012a).

29 India's thorium reserves are markedly larger than its uranium reserves.

2.4.1. Discursive

When identifying the discursive elements of the early Indian nuclear energy programme, three main themes seem to play an important role: the programme's socio-historical roots in a post-colonial state, Bhabha and his three-phase plan for nuclear development, and the lack of distinction between civil and military nuclear applications.

The nuclear energy programme originated shortly after India's independence, when the values of national pride, development and independence took centre stage across society as well as in government policy. There was a trend towards the large-scale nationalization of heavy industries and a general agreement that government was best at taking economic policy decisions and could bring about progressive change (Sovacool & Valentine, 2010). In this spirit of nationalization, the nuclear energy programme was seen as a prerequisite for modern development and energy independence. Indeed, supporting Bhabha's ideas for Indian nuclear energy, Nehru held the view that India's development should be articulated through techno-scientific advances and rationalization, of which nuclear energy was the Holy Grail. In other words, a centralist, technocratic ideology was at play in the making of the Indian nuclear energy programme (Sovacool & Valentine, 2010).

The idea of 'development towards independence' was a leading discursive element in the setup of the nuclear energy programme. The three-phase plan proposed by Bhabha in 1954 has proven to be a robust guideline: it still dictates the planning of Indian nuclear energy development, which is still aimed at increased energy independence through the eventual use of thorium. One reason the spirit of the early years of the programme lives on is the idea that '[o]ne has to attribute these achievements [in nuclear energy] entirely to the vision of Bhabha and Nehru, the tenacity of their successors in staying the course against all adversities' (Gopalakrishnan, 2002 pp. 391-392).

Another discursive aspect that characterized the Indian nuclear energy programme was the strict secrecy surrounding it. Nehru defended this secrecy, stating that it prevented sensitive information and/or technology getting into the wrong hands (Gopalakrishnan, 2002), be they those of competing nuclear energy developers or military opponents (e.g. Pakistan or China). Whether this exhausts the reason for secrecy, however, is debatable. In all, it has to be said that this secrecy seems to have helped 'protect' the programme by limiting the opposition's access to discursive resources.

The drive for domestic development and self-reliance led to a focus on indigenous technology (with international help early on). Thus, the nuclear energy programme was aimed at capacity building in Indian industry, in addition to energy production. Although limited reliability gave rise to several significant incidents during the first decades of the programme (Ramana, 2007; Tomar, 1980), secrecy and faith in central government control minimized their impact on the programme.

When asked in 1948 why both civil and military applications were cloaked in strict secrecy, Nehru had to confess: 'I do not know how to distinguish between the two', confirming the non-distinction between civil and military NEPT. This non-distinction has been seen as leaving open the possibility to use the nuclear energy infrastructure for military applications, a suspicion that gained credibility after India's 'peaceful nuclear explosion' in 1974, for which plutonium from civil reactors was used. After 1974, international cooperation was hampered by the weapons test, since India had not signed the Non-Proliferation Treaty. Building on the imagery of self-reliance and domestic development in the face of international adversity, however, the Indian nuclear energy programme kept receiving national support (Ramana, 2007).

2.4.2. Institutional

Many of the discursive aspects described above were aligned with the institutional arrangements through which the Indian nuclear energy programme took shape, and those institutional configurations have helped to carry the original aspirations into the present.

NEPT in India before 1983 was almost completely managed and regulated by the Department of Atomic Energy (DAE, established in 1954) and the Atomic Energy Commission[30] (AEC, established in 1958). The Bhabha Atomic Research Centre (BARC), which is part of the DAE, and its subsidiaries undertake most civil and military nuclear research. The permanence and power of this centralized nuclear establishment are partly a result of how it is organized: the AEC answers directly to the Indian prime minister, and the prime minister and his cabinet have generally had a 'virtual lock on policymaking' due to the govern-

30 Set up in 1958, the AEC became the intermediary between the DAE and the prime minister and is responsible for implementing government policy on nuclear matters and creating policy and budgets for the DAE.

mental structure (Sovacool & Valentine, 2010 p. 3807). Although the importance of the nuclear energy programme was already recognized in 1948 (roughly one-quarter of all Indian R&D spending was directed towards nuclear research from the 1950s to the 1980s (Tomar, 1980)), it was the 1962 Atomic Energy Act that really consolidated the institutional embedding of the establishment's power and the justification of secrecy. The fact that civil and military nuclear applications had not been conceptually distinguished repeated itself on an organizational level, where the DAE was responsible for both domains and BARC did most of the research into both domains. This management and research monopoly corresponded to the nuclear plant ownership and exploitation, whereby only central government or government-run institutions could engage in these activities, and had majority ownership.

One more institutional aspect of NEPT reinforced the reliance on Indian engineering and the focus on self-reliance: liability. The 1962 Atomic Energy Act did not mention liability or compensation in the event of an accident. This was not necessarily problematic for Indian nuclear power plants, as the government was officially liable in the end. Foreign nuclear technology sellers, however, would face full liability, which would make the economics of operating nuclear power plants uncompetitive, and were thus demotivated from entering the Indian nuclear energy field. All of this kept India on its three-phase technological trajectory.

2.4.3. Material

The material level of Indian NEPT corresponds to the discursive and institutional dimensions sketched above. Most of the Indian nuclear reactor fleet consists of PHWRs, which produce high ratios of plutonium as a fission product useable for energy production. This plutonium is necessary for the FBRs of the second phase. In addition, Indian PHWRs can run on natural uranium, which is important for self-reliance and independence from other countries. By choosing PHWRs for the Indian nuclear energy programme, the way to military applications was left open, as the plutonium from the PHWRs allowed for the construction of nuclear weapons.

India's nuclear energy programme relies on a closed fuel cycle (World Nuclear Association, 2012a). This allows for greater fuel efficiency by recycling in mixed oxide fuel (MOX), and is necessary for separating plutonium from spent fuel as input for the FBRs in phases two and three. This closed fuel cycle will, at least in principle, increase resource efficiency and independence, and lower the total volume and long-term risks of long-lived waste (Taebi & Kloosterman, 2008). Until then, however, spent fuel is stored for later use. However, as with all nuclear energy programmes, hazardous and long-lived waste is still produced as a by-product of nuclear energy production, which India plans to manage using deep geological disposal (Wattal, 2013).

India's PHWRs were the result of consciously domestic, centralized nuclear technology development, resulting in plants containing a high degree of Indian engineering. Development of the material elements of Indian NEPT has not been without its own set of difficulties, however, as not all materials and personnel education have always been up to par, leading to unsafe situations (Ramana, 2007; Tomar, 1980). In all, the material elements presented and the discursive elements – like national development, independence and technocracy (the intricate fuel cycle fitting well with a centralized and technocratic governance structure) – were well-aligned.

2.5. France

The early period of what could be called the most successful nuclear energy programme in the world (more than 75% of French electricity comes from nuclear fission (World Nuclear Association, 2012b)) presents a case of partial reversibility.

The French nuclear energy programme officially started in 1945 with the creation of the Commissariat à l'Energie Atomique (CEA) under the auspices of the Prime Minister, Charles de Gaulle. By 1956, the CEA's first real reactor was running (Hecht, 1998). The nuclear programme was part of rebuilding France after the economic devastation caused by WW2, of regaining the 'radiance of France' (Hecht, 1998). This also led to the nationalization of energy provision under government-owned Électricité de France (EDF) in 1946. The CEA and EDF had serious disagreements on France's nuclear future. This led them to different reactor designs, in which the ambitions of the agencies took material form. After two and a half decades of nuclear energy development, EDF managed to make the pressurized water reactor (PWR) the favoured reactor technology for the French nuclear programme.

2.5.1. Discursive

A number of discursive elements have been important to the development of the nuclear energy programme in France: the 'Radiance of France' that had to be regained, the connection of the programme and its artefacts to historical tradition and politics, French independence (including energy independence) and the limited distinction between military and civil nuclear activities.

After WW2, the Fourth Republic maintained the technocratic, managerialist and state-centric tendencies of the Third Republic. It aimed to restore the 'Radiance of France' (Hecht, 1998). This French 'radiance' was supposed to connect modern France with a more glorious past, a past of Louis XIV, chateaus and cathedrals, the now broken empire. Nuclear reactors were described in terms of modern cathedrals and chateaus, or were compared in size to the Arc de Triomphe (Hecht, 1998). Nuclear energy was not a break with the past; it was a modern continuation of French traditional ingenuity and grandeur. For this project to succeed, '*une attitude prospective*' (an attitude of inventive spirit) was needed, relying on 'large new technologies'[31] like nuclear technology. This necessitated systemic central planning but would allow France to once again become a successful, independent, flourishing nation (Hecht, 1998). National prowess, redevelopment and independence[32] became the values that would play an important role in the programme.

These values made the nuclear programme ideal for rebuilding a radiant France in more than one way. Even early on, military and civil nuclear applications were seen as benefitting from each other in a mutual dependence relationship (Schneider, 2010). Regaining the radiance of France through nuclear development and gaining increased independence meant achieving both energy independence and nuclear military prowess, which legitimated the State as responsible for the programme.

Nuclear energy's link with national pride meant that NEPT needed to be thoroughly 'French' and had to contribute to a radiant France. How that was to be done, however, was still open for discussion. Despite the original 'French' technology being *uranium naturel graphite gaz* (UNGG; natural uranium gas

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31 Technology was also conceptually separated from politics. It was supposedly neutral and rational. This is ironic, as the political dimensions of NEPT in France have had such impact on the programme's development (Hecht, 1998).

32 This drive for energy independence explains the drastic response to the 1973 oil crisis in the Messmer Plan, which aimed at lowering France's dependence on foreign oil.

graphite) reactors, the CEA and EDF disagreed on the intricacies in designing these reactors. Whereas the CEA developed its reactors from a more nationalistic and dual use (civil and military) perspective, EDF (without military objectives) redirected justificatory discourse in the 1960s towards economic factors (e.g. the 'competitive kilowatt-hour'), since it held that economically competitive nuclear energy was the best way to rebuild France (Hecht, 1998).

Lastly, access to information about nuclear issues was relatively limited (Schneider, 2010). Whereas general communication about nuclear energy was largely positive and often interwoven with nationalistic sentiment, critical voices often went unheard or unappreciated. As such, the discursive resources available to the public were limited and rather one-sided. This situation held at least until the substantial expansion of the nuclear energy programme in the 1970s, when more critical voices and public dissent arose.

2.5.2. Institutional

Much of the decision-making power over industrial and economic matters was in the hands of a technocratic elite: the 'Corps des Mines', a select group of *polytechniciens*[33] (engineers) that held important positions inside government and industry (Hecht, 1998; Schneider, 2010), with a clear distinction between policy insiders and outsiders (Teräväinen, Lehtonen & Martiskainen, 2011). This was also the case in the organization of the CEA (1945) and EDF (1946). The CEA was responsible for R&D concerning nuclear energy for both civil and military applications (in mutually beneficial configurations), including fuel cycle and nuclear reactor development. Its craving for the 'Radiance of France' explains its nationalism and the intricate connection between its nuclear activities and the then prevalent French politics (Hecht, 1998). EDF, on the other hand, was responsible for energy production and distribution, which included the design, construction and operation of nuclear power plants. However, EDF's activities had little or no military connection. Their idea of how the nuclear programme was to help achieve national goals was more liberal, international and generally much more focussed on the economics of nuclear energy (Hecht, 1998).

33 These engineers were being trained to be leaders, combining engineering, national pride and public service as values guiding their work (Hecht, 1998).

Since the French nuclear energy programme has largely escaped democratic parliamentary control[34] (Schneider, 2010), CEA and EDF engineers were involved in what Hecht (1998) describes as 'techno-politics'; that is, through the creation of institutional arrangements and technical artefacts, they were able to push their agendas for French radiance. This political conflict, hidden in technology, culminated in the '*guerre des filières*' (war of the systems), from which EDF's more 'apolitical', economically oriented programme emerged victorious with the PWR as dominant reactor technology at the end of the 1960s[35] (Hecht, 1998). Despite this victory for EDF, the rest of the nuclear fuel cycle, including mining, reprocessing and some enrichment, remained under the control of the CEA or its subsidiaries. This is interesting, since the disentanglement of nuclear power from military applications by EDF in preferring PWRs to UNGG reactors does not extend across the fuel cycle. France has had no fully separate civil and military nuclear fuel cycles (Schneider, 2010).

Concerning liability, in the past France had the lowest maximum liability limits in Europe (Faure & Fiore, 2008). If EDF had to insure itself against a worst-case scenario, the cost of electricity production would increase significantly (Schneider, 2010).

2.5.3. Material

The first eight reactors in the French nuclear energy programme were all of the UNGG type and were built by the CEA and EDF. However, they differed in subtle ways that allowed the CEA and EDF to materialize their political positions. CEA's first serious UNGG reactors (operational in 1956, 1959 and 1960, respectively) had markedly less energy output in favour of better plutonium production.[36] EDF, however, controlled the design of the non-nuclear parts of the reactors constructed at its site in Chinon (i.e. not the reactor core and fuel rods, which were the CEA's responsibility). As such, its first reactors (operational in

34 No legislation specific to nuclear energy was passed in France until 1991 (Schneider, 2010).

35 The first French PWR started operations in 1967 in Chooz, based on a Westinghouse license. In fact, the first French PWR at Chooz was not built by EDF, but was the result of a bid by Framatome (a private nuclear engineering firm), showing EDF's more economically liberal stance on nuclear power plant construction.

36 EDF did participate in CEA's first reactors, which strengthened its position as a nuclear player, but this could not prohibit 'below optimal' energy output as favoured by the CEA (Hecht, 1998).

1964, 1965 and 1966, respectively) were far better suited for more efficient energy production, which was in line with EDF's vision of how nuclear energy was to contribute to the 'Radiance of France' (Hecht, 1998).

EDF, with its discursive strategy of 'depoliticizing' nuclear energy's merits by strategically making economic efficiency and liberal market competitiveness important, managed to legitimate the 'foreign' PWR (developed in the USA; see section 2.6) as the most economically feasible candidate for French nuclear energy production. After the expansion of nuclear energy capacity after the oil crisis in 1973, total PWR capacity dwarfed that of other reactor types.[37]

However, the CEA's ambitions were still alive as the French had a closed fuel cycle in which they recycled part of their nuclear waste into MOX, which requires the separation of uranium and plutonium from nuclear waste. Their military and civil fuel cycles were not fully separated, discursively, institutionally or materially (i.e. they had been processed in the same waste treatment plants in Marcoule and La Hague since 1958 and 1976, respectively). In addition, the recycling of waste increases fuel efficiency, contributing to French energy independence. It also significantly lowers the total volume of long-lived waste to be disposed of in geological repositories, and this waste's radiotoxicity will decrease more quickly to non-hazardous levels compared to the waste from an open fuel cycle (Taebi & Kloosterman, 2008). Since 1978, France has been domestically enriching uranium for running PWRs (World Nuclear Association, 2012b), which adds to the country's energy independence.

As such, the discursive and institutional elements presented above are aligned with the material elements of French NEPT, with a relatively stable balance between the CEA's and EDF's techno-political aspirations. As such, the case of France shows how even slightly different aspirations can give rise to different material configurations, and how disalignments between discursive and institutional elements wielded by different actors can sometimes still be reconciled through material elements.

37 EDF currently operates 58 nuclear reactors, with a total generation capacity of 63 GWe, good for over 75% of the country's total electricity generation (World Nuclear Association, 2012b).

2.6. USA

The USA's civil nuclear energy programme has its origins in military research during WW2. This research resulted in the development of the atomic bomb, which was eventually used in the bombing of Hiroshima and Nagasaki (Parsons, 1995). After the war, in 1946, the Atomic Energy Act established the Atomic Energy Commission (AEC), which initially focussed almost exclusively on military nuclear development. Policy changes in the early 1950s, spurred by Soviet nuclear progress, culminated in Eisenhower's 'Atoms for Peace' speech in 1953 and the subsequent opening up of the nuclear programme to private parties for the construction and exploitation of nuclear power plants under the Atomic Energy Act of 1954 (Clarfield & Wiecek, 1984). By 1957, the first commercial reactor at Shippingport was online. The nuclear programme grew exponentially in the 1960s and early 1970s, but its expansion had practically ground to a halt by 1980 (Clarfield & Wiecek, 1984). Currently, 104 reactors provide about 19% of total electricity production in the USA (World Nuclear Association, 2013). The institutional elements that supported the programme's initial success, and its paralysis after 1980, are especially interesting.

2.6.1. Discursive

Before 1953, the American nuclear energy programme was dominated by military nuclear research and application. Confidentiality was so stringent concerning technical data that industry had little or no access to it and did not initiate nuclear power development in earnest (Clarfield & Wiecek, 1984). This changed drastically after Eisenhower's 'Atoms for Peace' speech in 1953. The discursive elements deployed in the speech were meant to help establish the USA's new place in a peaceful nuclear world, and to rhetorically distance itself from the other side in the Cold War: the Soviet Union.

Firstly, 'Atoms for Peace' was meant to contain the destructive force of the atom as had been witnessed in Japan only a few years before (Jasanoff & Kim, 2009), to 'strip its military casing and adapt it to the arts of peace'.[38] As such, the speech sought to make a very clear discursive distinction between civil and military applications of nuclear technology and indicated that they could indeed

[38] For a full transcript of the speech, see http://www.iaea.org/About/history_speech.html (accessed 29 March 2013).

be separated (Clarfield & Wiecek, 1984). This distinction marked a break with the previous decade, when the AEC considered military and civil nuclear development 'two sides of the same coin' (Lilienthal, 1947, p. 7). The speech was also meant to quell fear of the USA itself, a superpower with enormous destructive potential that was now committed to peaceful nuclear development[39] and would aid others by providing technology and know-how (and thus limit the Soviet Union's nuclear inlfuence in the world) (Jasanoff & Kim, 2009; Parsons, 1995).

Secondly, it implicitly and ideologically distanced Eisenhower's USA – the society of 'freedom, self-determination and life' (Jasanoff & Kim, 2009, p. 127) – from the Soviet Union, with its communist economic model and strong state influence in all aspects of life. This strengthened the call for nuclear privatization and limited government interference in a nuclear energy market. Similarly, the shroud of secrecy was lifted a little in 1954, as industry needed information in order to design, develop, construct and exploit nuclear power plants. This opened up possibilities for private industry by granting them discursive resources not previously available to them.

2.6.2. Institutional

Since nationalized energy provision would not fit the ideological climate of the times, the USA's nuclear energy programme relied on industry and private utilities to design, build and operate nuclear power plants. This was reflected in the way the Atomic Energy Commission (AEC) was set up in 1946: it was responsible for the regulation, R&D and promotion of both military and civil nuclear power (Clarfield & Wiecek, 1984), but was forbidden to build or operate full-scale power plants, and had to rely on industry and utilities to do so instead (Cowan, 1990). Before 1954, private industry's access to technical information on NEPT was severely restricted and as such, the industry did not develop. Meanwhile, the AEC focused its efforts mostly on military nuclear power, culminating in the development of nuclear naval propulsion with PWRs. Once industry was granted access to technical nuclear information in 1954, the AEC could focus on facilitating the development of a civil nuclear industry (Clarfield & Wiecek, 1984). Although privatization was important, liability was set by the

39 This adherence to peaceful development held true only insofar as the USA's military and civil programmes were materially separated after 1954. The Cold War still saw a serious American nuclear weapons build-up.

Price-Anderson Act of 1957 at $60 million for the company in question (because private insurers would not insure for a larger amount), and $500 million was committed by the federal government in the event of an accident. This provided a safe investment environment for private industries, but required considerable government warrant (Clarfield & Wiecek, 1984). This may seem to go against a truly private nuclear energy industry, but there was national interest in its development too, as put forward in 'Atoms for Peace': exportable NEPT to strengthen the USA's international position in nuclear affairs (Jasanoff & Kim, 2009).

The AEC's dual role as promoter and regulator put it into a conflict of interest between the interests of the nuclear industry (promotion) and the interests of US citizens (safety regulation), and the AEC has indeed at times traded off its regulatory responsibilities against industrial success in order to enable the latter. For example, over the course of the 1950s and 1960s, the AEC and the industry had been rather conservative with funding and publishing research into the risks of nuclear power (Clarfield & Wiecek, 1984). For instance, the AEC's decision to not fully disclose the results arising from the 1964 revision of the 1957 WASH-740 report on the risks of nuclear energy was partly inspired by the detrimental effects the increased risk estimates in the revision would have on nuclear industrial development (Clarfield & Wiecek, 1984; J. S. Walker, 1992). On top of this, the multitude of reactor designs and operating procedures employed by private industry made it especially difficult to overview the specific risks for every situation and made licensing procedures slow. However, risks were not the only thing that could make or break the industry. Cost prospects in the 1950s and 1960s were extremely optimistic, assuming that increased experience and economies of scale would push nuclear energy prices down to a level 'too cheap to meter'.[40] It was thought that the costs of nuclear energy production would end up well below those of conventional fuels, like coal. This idea took on a life of its own as the industry and the AEC echoed one another's optimistic cost estimates. Despite the unrealistic assumptions on which this optimism was based, it had a profound effect, namely it helped start a bandwagon market for nuclear power with orders for plants rolling in faster than the AEC could license them

40 The term was coined by Lewis Strauss, then the chairman of the AEC, in a 1954 speech to the National Association of Science Writers (Strauss, 1954). Although not to be taken literally as a realistic cost estimate for nuclear fission, it has become iconic of the economic optimism at the time concerning nuclear power and its future.

(Carlfield & Wiecek, 1984). However, as the 1970s began, nuclear energy faced increased contestation from the environmental movement (especially in the wake of the National Environmental Policy Act of 1970). This led to increased safety standards, and the realization that the economics of nuclear energy were much worse than previously assumed, and by 1973 the number of orders had dropped considerably (Parsons, 1995). It is interesting to note that while the courts generally favoured the AEC and its decisions during the 1950s and 1960s, the judiciary culture in the USA provided a legitimate realm for contestation (Clarfield & Wiecek, 1984). This contestation indirectly helped lead to stringent regulation and helped spur the criticism of the AEC, laying bare the conflict of interest it operated on.

By 1974, the AEC was under such strong attack for unduly favouring the industry it was meant to regulate that it was dissolved. Regulation, licensing, materials management and the setting of safety standards were brought under the wing of the Nuclear Regulatory Commission (NRC), and the promotional activities were assigned to the Energy Research and Development Administration (ERDA). As a result, and under increasing societal pressure, regulation became even more stringent, risks were more systematically investigated[41] and costs rose dramatically. The Three Mile Island nuclear accident in 1979 was the proverbial nail in the coffin of what twenty years earlier had been an exponentially growing nuclear energy industry (Parsons, 1995).

2.6.3. Material

The fact that in its early life the AEC focused on military applications of nuclear energy had led to an initial organization of industry around and increased experience with PWRs (Cowan, 1990). Despite the AEC's early experimentation in the 1950s with a number of different reactor types (Parsons, 1995), the urgency lent to the programme by the 'Atoms for Peace' drove the nuclear industry towards a solution that was relatively reliable in the short term due to this experience: PWRs.

The clear distinction in 'Atoms for Peace' between military and civil nuclear power is also reflected in the abandonment of reactors specifically designed for

41 For example, despite critique of the uncertainties of the underlying research, the 1975 WASH-1400 or 'Rasmussen' report was much further developed than its 1957 counterpart and introduced the methodological basis for modern probabilistic risk assessment.

dual use, which were considered in the early years of the AEC (Clarfield & Wiecek, 1984). Moreover, 'Atoms for Peace' also set the stage for the open fuel cycle in two main ways. By urging privatization and making cost a critical aspect of nuclear power generation, it assisted the allegedly cheaper open fuel cycle (Deutch et al., 2003). Closed fuel cycles also leave more room for military abuse, by reprocessing waste and extracting fissionable materials suited for military applications (Deutch et al., 2003), a goal not aligned with the distinction between civil and military nuclear power so adamantly emphasized by Eisenhower in 1953. Finally, the institutional arrangement of a privatized nuclear power industry with a plethora of specific plant designs and operations probably helped push the USA towards an open fuel cycle, as the management of a closed fuel cycle would be significantly more difficult than under a centralized, uniform programme such as that in France or India. As alluded to above, however, this open fuel cycle produces higher volumes of high-level radioactive wastes[42] that also remain radiotoxic for significantly longer than their French and Indian counterparts (Taebi & Kloosterman, 2008).

2.7. Irreversibility of NEPT in India, France and the USA

As the historical narratives above show, these three countries have successfully developed a domestic nuclear energy programme, and have put in place a wide assortment of discursive, institutional and material elements in the process. In this section, both the stable constellations of elements implicated in circuits of reproduction as well as important disruptive events will be summarized and discussed in terms of the reversibility/irreversibility of NEPT.

2.7.1. India

Indian NEPT development is a good example of a circuit of reproduction that, owing to sufficient alignment between its elements and adequate protection through asymmetries in resources, experienced little disruption in its early decades. In the years following independence, a number of discursive, institu-

[42] It needs to be noted that while volumes of high-level radioactive wastes are larger for the open fuel cycle, total waste volume needs not be. Reprocessing in the closed fuel cycle produces additional low- and intermediate-level radioactive wastes (Deutch et al., 2003)

tional and material elements were introduced that would eventually come to define Indian NEPT. These elements are summarized in table 2.2.

Table 2.2 Stable set of elements constituting Indian NEPT

Discursive	Institutional	Material
National pride	Technocratic governance	Indigenous development of material elements
Development towards independence	Centralized decision-making power and R&D (DAE)	PHWRs: use of natural uranium increases independence from other countries
Development through techno-scientific advances	Centralized planning and responsibility for construction according to the three-phased plan (DAE and subsidiaries)	PHWRs: produce plutonium for the second phase
Nuclear energy as symbol of development	Little democratic control due to the DAE directly reporting to the Prime Minister	Closed fuel cycle: recycling increases resource efficiency
Faith in government for policy decisions	DAE and BARC executing both civil and military research	Closed fuel cycle: reprocessing allows for extraction of fuels for phases two and three
Bhabha's three-phase plan	Government majority ownership	Closed fuel cycle: reprocessing allows for extraction of plutonium for military purposes
Non-distinction between civil and military application	Unlimited liability: discourages foreign input	Phase two: FBRs
Secrecy	Capacity building in Indian industry	Phase three: Thorium-based reactor fleet

1945-1950s
1960s-1980s
Promised

These were initially limited to discursive and institutional elements, aligned with India's state-driven technology-based development. Bhabha's three-phase plan formed a strong shared aspiration around which action could be organized. According to the conceptualization of technology development presented above, alignment between generally shared aspirations and specific other elements, as well as amongst these elements themselves, would already provide a strong impetus for agents to reproduce these structures through action (giving rise to the abovementioned circuits of reproduction). Additionally, possible disalignments between these elements (e.g. issues of safety or environmental degradation) would arguably have not given rise to disruptive events. This is due to asymmetries in discursive and institutional resource availability for nuclear and non-nuclear actors. Secrecy limited the discursive resources available to non-nuclear actors and prevented disalignments from coming into play. A concentration of institutional resources with the centralized and technocratic nuclear establishment (e.g. decision-making power concerning acceptable risk levels, and licensing and construction outside parliamentary control) limited the possibility for disruptive action even if disalignment had been recognized. As such, the programme was 'protected' from disruption and insiders could add novel elements (mainly material ones after 1960), aligned with the ones already in place. All of this resulted in a relatively stable circuit of reproduction of Indian NEPT. Seeing the difficulty of breaking the circuits of NEPT reproduction (technology development) in India due to the structural setup of this technology, the Indian case offers a good example of largely irreversible NEPT.

2.7.2. France

The case of France is interesting because, due to disruptive events, it has undergone partial reversal. While the nuclear programme as a whole has not been halted (i.e. its circuit of reproduction was not broken), some specific elements have significantly changed over the course of NEPT development, the most prominent of which is the change from UNGG reactors to PWRs. The period between the end of WW2 and the early 1960s marks the pre-disruption phase of the French nuclear programme (see table 2.3).

Table 2.3 Stable set of elements constituting French NEPT before 1960

Discursive	Institutional	Material
Rebuilding the 'Radiance of France' after WW2 through NEPT	Technocratic governance	Indigenous design and production of material elements
Necessity of central planning for large new technologies	Little democratic input	UNGG reactors, mainly aimed at plutonium production
Nuclear energy as a modern continuation of French traditional ingenuity and grandeur	Centralized R&D and decision-making power (CEA), on both civil and military applications	Closed fuel cycle: reprocessing increases resource independence through spent fuel recycling
Nuclear energy technologies must be thoroughly 'French'	CEA responsible for reactor design	Closed fuel cycle: reprocessing allows the extraction of plutonium for military purposes
Technology and nationalistic politics interwoven	CEA responsible for rest of fuel cycle	
Military and civil applications reinforce one another and are mutually dependent	EDF responsible for energy production and redistribution	
Secrecy		

1945-1950
1950-1960

Similarly to the Indian programme, one can see an initial introduction of aligned discursive and institutional elements largely in line with broader societal dynamics. Also similar is the protection of the programme through secrecy and asymmetrical access to resources between agents inside and outside the nuclear establishment. However, change came from inside the establishment. Through incremental adjustments to the UNGG reactors, and the successful legitimation of the 'competitive kilowatt-hour' as the proper operationalization of how nuclear energy was to contribute to the 'Radiance of France', EDF managed to undo a number of previously central elements of French NEPT. This led to a partly different stable set of elements (see table 2.4).

Table 2.4 Stable set of elements constituting French NEPT after 1960

Discursive	Institutional	Material
Rebuilding the 'Radiance of France' after WW2 through NEPT	Technocratic governance	EDF's UNGG reactors, better suited for efficient electricity production (before 1968)
Necessity of central planning for these large new technologies	Little democratic input	PWRs based on American Westinghouse design (after 1968)
The competitive kilowatt-hour: Depoliticization of nuclear reactors through appealing to economic efficiency	Centralized decision-making power	PWRs optimized for energy production
Energy production and other nuclear applications separated	CEA responsible for rest of fuel cycle	Closed fuel cycle: increases resource efficiency
Secrecy	EDF responsible for energy production and redistribution	Closed fuel cycle: increases resource independence through spent fuel recycling
	EDF responsible for nuclear power plant construction and operation	Closed fuel cycle: allows extraction of plutonium for military purposes
	Favourable liability arrangement for EDF and CEA	Dual use of reprocessing infrastructure

Elements retained from before 1960
New elements after disruption by EDF

EDF, building on the institutional resources afforded by its position as a nuclear player, managed to discursively depoliticize nuclear energy by replacing its necessary 'Frenchness' with an 'objective' measure of economic efficiency. This was materialized in EDF's early UNGG reactors at Chinon. In doing so, it managed to sever the formerly intrinsic connection between civil and military use of nuclear power plants, and gained institutional resources by now being responsible for nuclear power plant construction and operation. Despite this, the resulting configuration is largely aligned with the aspirations of both EDF and the CEA, since the closed fuel cycle (under the auspices of the CEA) provided opportunities for both military applications and increasing efficiency.

The circuit of reproduction of French NEPT was not broken. Rather, certain structural elements were undone and replaced, which opened up various possibilities for future development. EDF's disruptions arguably even helped the French nuclear energy programme achieve its success. Still, since significant disruptions led to the undoing of specific elements of French NEPT (i.e. diminished their reproduction in favour of the elements that EDF introduced), French NEPT development is an example of the partial reversal of NEPT.

Table 2.5 Stable set of elements constituting the USA's NEPT roughly between 1953 and 1970

Discursive	Institutional	Material
Atoms for Peace: putting the atom to peaceful use	Nuclear privatization: industry responsible for designing, building and operating nuclear power plants	Dominance of PWRs (most ready for use by industry in the 1950s)
Atoms for Peace: sense of urgency in developing domestic nuclear energy industry	AEC responsible for both regulation and promotion of nuclear energy	Differences between specific PWRs
Atoms for Peace: distancing USA from the Soviet Union through 'freedom, self-determination and life'	Regulation loose enough as to allow for industry development	Open fuel cycle: cheaper for industry
Very clear distinction between civil and military applications	AEC/industry echo chamber for optimistic prospects for nuclear energy	Open fuel cycle: less risk of dual use of nuclear energy infrastructure
Nuclear energy that is safe and 'too cheap to meter'	Little possibility for legal contestation	Open fuel cycle: facilitates management of spent fuel from a variety of private suppliers
Limited confidentiality and secrecy: open for enabling industry, secretive about things that inhibit its growth	Favourable liability arrangement for industry	Open fuel cycle: requires less government intervention

2.7.3. USA

Of the three countries discussed, the USA is the only one in which the expansion of the nuclear energy programme came to a halt. From 'Atoms for Peace' in 1953 until the early 1970s, the USA's nuclear energy programme rapidly expanded and NEPT largely consisted of the structural elements listed in table 2.5. However, as the 1970s set in, a number of these elements were no longer applicable. For example, the opening up of the judiciary system as a legitimate realm of contestation and the dissolution of the AEC (and the assumption of its responsibilities by the NRC and ERDA) significantly altered the distribution of institutional resources in favour of more democratic control and outsider influence (eventually leading to stricter regulation under the NRC). Non-nuclear actors could then act upon the disalignments arising in NEPT over the course of the 1960s and 1970s:

- Firstly, there was an important disalignment between continuously increasing costs on the one hand, and a competitive and privatized nuclear industry with relatively little government intervention on the other.
- Secondly, guaranteeing that nuclear energy will be both safe ('Containing the Atom') and cheap ('Too Cheap to Meter') proved difficult, despite what the AEC had long espoused. Trade-offs were necessary. Indeed, when regulations, safety standards and bureaucratic demands became more stringent under the NRC, costs rose so dramatically that private industry lost its domestic interest, evidenced by the fact that the flow of applications for new nuclear power plants came to a halt at the end of the 1970s, after the Three Mile Island accident had vividly confirmed that absolutely safe nuclear power was hardly guaranteed.[43]

In other words, whereas the institutional setup of the nuclear programme (privatized nuclear industry) was important for its rapid growth in the 1950s and 1960s, that very same setup ceased to work once elements that disaligned with its working principles arose. So, these disalignments can be said to have broken the USA's circuit of NEPT reproduction, insofar as further implementation of

[43] Although the health effects of the Three Mile Island accident were minimal, its symbolic confirmation of doubts concerning safety held by those critical of nuclear energy provided them with the discursive resources to legitimately question the nuclear energy programme.

NEPT in society has ceased. As such, the USA's NEPT has not proven completely irreversible.

However, is this sufficient to truly speak of technological reversibility? After all, existing nuclear power production continued to generate nuclear energy as well as radioactive waste, and specific discursive elements (e.g. the USA as a nuclear state) and institutional elements (e.g. nuclear industry and the NRC) are still present. To truly speak of reversible NEPT, it seems that an additional requirement is required, which is discussed below.

2.7.4. Conditions for reversible NEPT

Some preliminary insights concerning reversibility in NEPT development can be distilled from the analysis. As alluded to in the previous section, I argue that not one but two central conditions need to be met for NEPT to be considered truly reversible:

- The ability to stop the further development and deployment of a NEPT in a society; namely it has to be possible for the circuit of NEPT reproduction to be broken. For this to happen, it seems important to have disalignments between structural elements and a relatively symmetrical distribution of resources between agents (including the possibility to create and act upon disalignment).
- The ability to undo the undesirable outcomes of the development and deployment of those NEPT. Since the outcomes of NEPT development are its structural elements, the ability to undo those whether or not the circuit of reproduction has been broken would satisfy this condition. This includes the risks posed by radioactive wastes, however difficult to 'undo' these risks may be.

The analysis above has mainly highlighted the first condition (i.e. stopping NEPT development). The largely aligned sets of elements, coupled with specific asymmetries in resource distribution, were identified as making NEPT development more irreversible by reinforcing their reproduction. However, if a circuit of NEPT reproduction is actually broken, the ability to undo possibly problematic outcomes[44] would surely be desirable and necessary to truly speak of technological reversibility. This ability was apparently lacking in the USA after its circuit of NEPT reproduction was broken when further implementation of NEPT halted after the 1970s. Moreover, even if NEPT reproduction is largely acceptable, the second condition would allow for targeted partial reversibility of those elements of NEPT that are found to be problematic, like EDF managed to do in France. Finally and unsurprisingly, this means that without an adequate solution to the problem of nuclear waste, it is impossible to speak of reversible NEPT. However, as the analysis above has shown, different NEPT produce radioactive wastes with different characteristics. On top of this, solutions are more likely to be implemented if aligned with NEPT's other discursive, institutional and material elements. As such, despite the fact that high-level radioactive waste is very persistent no matter what fuel cycle it is a by-product of, it would seem that what constitutes an adequate and practical solution to this problem is likely to be context-dependent. Of course, all the above leaves unanswered the question how exactly these two conditions are to be met, but answering it is the topic of future work.

Lastly, it needs to be noted that a dilemma seems to haunt a call for reversibility: if, as Orlikowski (1992) argues, the objectification and institutionalization of technology is essential for its ability to 'do work', then the reversibility and the efficacy of a technology are apparently at odds. Despite its potential importance if problems with NEPT arise, the complete reversibility of NEPT might make a circuit of NEPT reproduction difficult (if not practically impossible), hence inhibiting the development of NEPT in the first place. As such, further research should elaborate on how efficacy and reversibility are to be balanced across a process of technology development.

2.8. Conclusion

In order to properly analyse irreversibility of NEPT, this paper conceptualized NEPT development as a process of structuration involving human aspirations. According to this conceptualization, NEPT consist of a relatively stable set of discursive, institutional and material elements, stretching across time and space

44 For example, a coupling of civil and military nuclear use, specific asymmetrical resource distributions between elites and others, or even existing infrastructure or the production of radiotoxic artefacts like spent fuel.

through recursive implication by social actors. They are delineated from the rest of the social system by their identification as belonging to NEPT. Technological irreversibility arises when these elements get caught in circuits of NEPT reproduction.

This conceptualization of technology development was subsequently used to structure an analysis of the early decades of NEPT development in India, France and the USA. It was observed that the alignment of the structural elements of NEPT and a concentration of resources with those agents reproducing these elements were both important factors in keeping circuits of reproduction running. Indian NEPT exhibits both these characteristics, providing a good example of largely irreversible NEPT. However, disalignments combined with changes in resource availability in favour of dissenting voices provide the conditions for disruptive events. In France, EDF managed to create disalignments in French NEPT by introducing new structural elements (e.g. the economic kilowatt-hour and the foreign PWRs). This eventually led to the partial reversal of French NEPT (i.e. some of its structural elements were undone and replaced by others). In the USA, the circuit of NEPT reproduction was actually broken when legitimate realms of contestation opened up, which made acting upon disalignments possible. Despite this, specific elements of the USA's NEPT persist to this day.

The results of the analysis prompted the formulation of two conditions for reversible NEPT: 1) the ability to stop the further development and deployment of a NEPT in a society, and 2) the ability to undo the undesirable outcomes of the development and deployment of those NEPT, which includes the risks posed by radioactive wastes and spent fuel. These conditions might help us in developing reversible NEPT, although the extent to which this is desirable is unclear given the possible tension between complete reversibility and technological efficacy.

3 Responsible Innovation In Light of Levinas: Rethinking the Relation between Responsibility and Innovation

To date, much of the work on Responsible Innovation (RI) has focused on the 'responsible' part of RI. This has left the 'innovation' part in need of conceptual innovation of its own. If such conceptual innovation is to contribute to a coherent conception of RI, however, it is crucial to better understand the *relation* between responsibility and innovation first. This paper elucidates this relation by locating responsibility and innovation within Emmanuel Levinas' phenomenology. It structures his work into three 'stages', each described in terms of their leading experience and objectivation regime. This analysis identifies a need for constant innovation of political and technological systems, originating from and motivated by our responsibility to others. It also shows the relation between responsibility and innovation to be threefold: foundational, ethical, and structural. These insights could help RI to avoid some pitfalls of 'regular' innovation, and provide moral grounding for important aspects of RI.

3.1. Introduction

The past decade has seen a fair amount of theorizing on the concept of Responsible Innovation (RI)[45]. RI is an approach to research and innovation that aims to improve the "(ethical) acceptability, sustainability and societal desirability of the innovation process and its marketable products", and does this by getting a wide range of societal actors and innovators to become "mutually responsive to each other" (von Schomberg, 2011 p. 9).

This new approach is often deemed necessary in view of the "grand challenges" of our time, such as climate change, the need for sustainable agriculture,

[45] This is sometimes more inclusively formulated as Responsible Research and Innovation (RRI).

secure and clean energy, etc.[46] (von Schomberg, 2013). These grand challenges come with large uncertainties (in terms of both problem definitions and possible solutions), serious epistemic and moral disagreements among actors, and the need for a wide variety of those actors to successfully cooperate. In short, these are wicked problems (Horst and Webber, 1973). In the face of such problems, current regulation-based systems of innovation governance are said to be inadequate because they rely on an outdated responsibility regime based in predictability, consequentialist reasoning and top-down decision-making (Grinbaum and Groves, 2013; Owen et al., 2013).

This critique points to a deficit in the "process" dimension of innovation that hinders the achievement of good outcomes (i.e., the "product" dimension)(von Schomberg, 2013). This realization is reflected in the fact that most attempts to theorize about responsible innovation have focused on the 'process' dimension, often conceptualizing and/or formalizing more responsible and inclusive processes of stakeholder engagement or formulating the characteristics that would make an innovation process more responsible (e.g., Blok, 2014; Owen et al., 2013; Pellé, 2016; cf. Thorstensen & Forsberg 2016). In other words, research has often focused on formalizing the 'responsible' part of RI.

For all that, the focus on responsibility has allegedly left the other half of the RI dyad (i.e., innovation) problematically undertheorized (Blok & Lemmens, 2015). This in turn led to a situation where the underlying assumption in RI research and practice has often been that "responsible innovation = regular innovation + stakeholder involvement" (ibid p. 20). Given that this 'regular' notion of innovation is likely to hinder the achievement of responsible outcomes (Blok & Lemmens, 2015), replacing it with a notion of innovation more specifically tailored to RI could provide a promising strategy for bolstering RI. This would in turn require a novel, RI-specific (re)conceptualization of innovation.

In addition to responsibility and innovation, however, there is another aspect to the RI dyad that runs the risk of remaining obscure despite the fact that its elucidation could be beneficial for a coherent conception of RI: the *relation* between RI's constitutive terms. Indeed, it stands to reason that coming to grips with the relation between responsibility and innovation is a crucial step towards conceptualizing and formalizing both of these terms in such a way that they can

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46 See https://ec.europa.eu/programmes/horizon2020/en/h2020-section/societal-challenges, Accessed 22 September, 2016.

be properly integrated. As such, this paper aims to shed some light on the relation between responsibility and innovation. It does so through a process of partial *deformalization*[47], rather than reflecting on precise processes, outcomes, rules or definitions. That is, it reveals the crucial importance of responsibility and innovation as well as the nature of the relation between them by providing a phenomenological account of social existence in terms of the concrete experiences that form its foundation.

The account presented in this paper locates both responsibility and innovation within the broader structure of the ethical phenomenology of Emmanuel Levinas. Up to this point, Levinas' philosophy has only seen limited application in RI research, i.e., in considering the implications of his ground-breaking work on the nature of responsibility for the 'responsible' part of RI[48] (Blok, 2014; Costello & Donnellan, 2008; Pellé & Reber, 2016). However, I argue that Levinas' *oeuvre* also points to a need for the constant innovation of technological and political systems, originating from *and* motivated by our responsibility to others. Section 2 first presents Levinas' existential analytic through the lens of a three stage model that locates responsibility vis-à-vis technology and politics and shows that the latter are in constant need of change. In section 3, innovation is located in the third stage of the model, and its relation to responsibility is further specified. Finally, section 4 discusses a number of implications of the relation between responsibility and innovation for RI, and our conception of innovation therein. Additionally, it shows that conceiving of the relation between responsibility and innovation in this way is compatible with and provides additional moral grounding for some already recognized aspects of RI.

47 'Deformalization' describes Levinas' efforts to move some concepts (especially that of 'time' (e.g., Levinas, 1998a p. 175)) away from the schematisms, abstractions or ontological systematizations in terms of which they are usually described, and back to the concrete experiences that ground them (the interruption of egological existence by the Other being chief among them).

48 Blok's use of Levinas' concept of responsibility as the putting into question of the Ego and its totalizing tendencies is probably the most developed Levinasian account of (part of) RI (Blok 2014).

3.2. Responsibility and the Need for Technological and Political Change in Levinas

The task for the following sections is to shed light on the relation between responsibility and innovation. This is done by locating them within the framework of the philosophy of Emmanuel Levinas[49], who provides a phenomenological description of human experience, discovering the source of ethics in the relationship to the human Other. This is the point of departure for the interpretation of the world, for politics and for technology (called Levinasian *techno-politics* in this paper). On this account, politics and technology both have their foundation in responsibility and, as I argue in this paper, are in infinite need of innovation. To show this, it is necessary to draw out more clearly Levinas' thinking on technology and its relation to responsibility and politics. To this end, this section is structured according to a number of 'stages' that are roughly recognizable but not explicitly present in Levinas' existential analytic, which describes the structure of subjectivity from its first separation from the outside world towards its problematic political existence[50]. In this paper, three such stages are proposed, each being a precondition for the next one: 'Origins of the I: Egoism', 'In Light of the Other: Ethics', and 'Comparing Incomparables: Justice'. For each stage, two important aspects are discussed below. First, a stage's *leading experience* describes the experience that is both constitutive of that stage as well as motivates, animates and gives direction to it. Secondly, a stage's distinctive *objectivation regime* is concerned with how its leading experience is objectivated in the outer world through action. That is, it describes how a stage takes 'concrete'[51] shape. For example, the second stage describes how its leading

49 This structure is mainly inspired by Levinas' *Totality and Infinity* (Levinas, 1969), amended with other works where applicable. I take *Totality and Infinity* to provide the most helpful thematic structure to think about how the experiences most central to Levinas' work are objectivated in the 'outer world'.

50 The irony of such a 'technical' presentation of Levinas' thought so as to locate his stance on technology and innovation is not entirely lost on me. For reasons of both brevity and clarity, however, this simplified account seems appropriate nonetheless. To counterbalance this (over-)systematization and let some of the sensitivity and atmosphere of Levinas' initial analysis shine through, I liberally cite Levinas' own writings.

51 As a phenomenologist, Levinas considers experience to be concrete and not abstract. However, throughout this paper, the word 'concrete' is used in terms of (experiences that involve) active and material engagement with the outer world, similarly to how Levinas does when he writes that "[t]he whole of the civilization of labor and possession arises as a concretization of the

experience, i.e., responsibility, is objectivated as giving away my possessions to those to whom I am responsible. Describing the three stages in this manner connects the more commonly considered elements of Levinas' work (i.e., enjoyment, responsibility and justice) to their all too often overlooked concrete correlates concerning the comprehension and handling of the world around us, culminating in the aforementioned techno-politics in the third stage (see table 3.1).

Table 3.1 Three 'stages' in Levinas' existential analytic

	=> is a precondition for =>		
Stage	**Origins of the I: Egoism**	**In Light of the Other: Ethics**	**Comparing Incomparables: Justice**
Human-orientation	I	Other	Third
Leading Experience	Enjoyment	Responsibility	Justice
Objectivation Regime	Possession	Gift	Techno-Politics

3.2.1. Origins of the I: Egoism

The first 'stage' I glean from Levinas' phenomenological analysis is that in which the 'I' first arises as an existence in its own right, separated from the world. This fundamental separation comes about in the experience of *enjoyment*, which gives rise to the juxtaposition of the enjoying I on the one hand and the world it takes in and enjoys on the other, their relation described as a "living from" (Levinas, 1969 p. 110)[52]. Notably, such enjoyment does not belong to the order of knowledge, thought or practical problem-solving, but rather that of sentiment. That is, it does not invite a representation of the world but rather operates as *sensibility*. It is "beyond instinct, beneath reason", the "very narrowness of life" (Levinas, 1969 p. 138). It is quite simply the savoury enjoyment, in the moment, of "thinking,

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separated being effectuating its separation. But this civilization refers to […] existence proceeding from the intimacy of a home, the first concretization" (Levinas, 1969 p. 153).

52 Levinas emphasizes enjoyment as *the* foundational experience for the ego: "enjoyment is not a psychological state among others […] but the very pulsation of the I" (Levinas, 1969 p. 113).

eating, sleeping, reading, working, warming oneself in the sun"[53] (Levinas, 1969 p. 112) which provides "nourishment, as a means of invigoration" (Levinas, 1969 p.111). As such, enjoyment describes the I as an ego that takes the world into itself, consuming it and making it part of itself. This egoistic[54] orientation describes "a withdrawal into oneself, an involution" (Levinas, 1969 p. 118). Such an ego can be said to exist for itself: not conscious as "a representation of self by self [but rather] for itself as in the expression 'each for himself'" (Levinas, 1969 p. 118). As such, the leading experience of the 'Origins of the I: Egoism' stage is self-sufficient, unreflective, pre-conscious enjoyment; a nourishment that produces satisfaction (rather than fulfilling articulated needs); a life that lives off a love of life itself.

However, enjoyment is beset with "concern for the morrow" (Levinas, 1969 p. 150), with uncertainty about its future since enjoyment does not provide the objective conditions necessary for its own continuation. Those conditions are made possible only by labor and possession, both of which refer to a dwelling, the intimacy of a home, "the first concretization" (Levinas, 1969 p. 153). From the interiority of the home, the separated I can recollect itself, look out the window upon a world that is now at a distance. This makes possible "a look that dominates, [...] the look that contemplates"; the outside world is now "at the disposal of the I—to take or to leave" (Levinas, 1969 p. 156). This 'taking' of the elements is the taking-*possession* through labour. Labour, which is the "destiny of the hand" (Levinas, 1969 p. 159)[55], draws things from the elements and relates them to the I's own ends. It does so, however, by "separating it from immediate enjoyment, depositing it in a dwelling, conferring on it the status of a posses-

53 Enjoyment underlies every experience of the things around us, even of (technological) tools used pragmatically, whose existence "is not exhausted by the utilitarian schematism that delineates them as having the existence of hammers, needles, or machines" (Levinas, 1969 p. 110).

54 Levinas' conception of egoism should not be read as a condemnable selfishness in the face of others. It is pre-conscious and unreflective, and thus naïve rather than evil.

55 The labouring hand, Levinas tells us, is "no longer a sense-organ, pure enjoyment, pure sensibility, but is mastery, domination, disposition. An organ for taking, for acquisition, it gathers the fruit but holds it far from the lips, keeps it, puts it in reserve, possesses it in a home" (Levinas, 1969 p. 161). This is a telling illustration of Levinas' recognition that enjoyment, dwelling, habitation and possession are only possible in an existence that is a body.

sion" (Levinas 1969, p. 159)[56]. This, then, constitutes the *objectivation regime* of this first stage: the I secures its future by taking possession of the elements through labour, which transforms them into "raw materials" (Levinas 1969, p. 159) and relates them to the I's egoist ends.

In sum, the leading experience of the first stage is enjoyment, while its objectivation regime consists of possession that ensures enjoyment in the face of an uncertain future. However, despite separating the I from the non-I, enjoyment and possession through labour are still a movement towards oneself. That is, since the relation with the non-I is exhausted by that which is already enjoyed and possessed by the I[57], the I cannot by itself become conscious of itself. For that to happen (and thus open up the possibility of responsibility, politics, technology and innovation), the I has to be put into question by that which transcends it, i.e., that which lies beyond its grasp, that which it cannot contain. Levinas locates this transcendence in the idea of infinity, which already overflows any thought or conception one could have of it and thus invites transcendence. Notably, however, the experience of infinity is not primarily an abstract or theoretical affair. Rather, "[t]he idea of infinity is the social relationship" (Levinas, 1987 p. 54), i.e., infinity manifests itself in responsibility to the human Other, in ethics.

3.2.2. In Light of the Other: Ethics

The second stage, "In Light of the Other: Ethics", is concerned with the themes on which Levinas spent most of his philosophical energy. It presents the transition from the pre-conscious 'I' of the first stage to a subject that is capable of both reflection as well as knowledge of the things of the world.

This transition, Levinas explains, is made possible by coming face to face with infinity. That is, the I that was preoccupied with securing enjoyment through possession is now faced with an experience that lies permanently beyond its understanding and resists its attempts at mastery; it is faced with an Other that is infinitely beyond its grasp. Unlike possessions, this Other does not

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56 By selectively suspending the elemental in the home, possession com-prehends [*comprend*] or *grasps* the being of the existent. It is through labour and in possession that the thing first arises. (Levinas, 1969 p. 158).

57 I regrettably have to exclude what would undoubtedly be an interesting discussion of Levinas' concept of the *il-y-a*.

arise from labour. Rather, the Other *expresses itself* (Levinas, 1969 p. 49-52) and in doing so, "presents itself as human Other" (Levinas, 1996 p. 12)[58].

The human Other, irreducible to the I, its thoughts and its possessions (Levinas, 1969 p. 43), calls into question the I's spontaneity. The Other is the "judge judging the very freedom" (Levinas, 1969 p. 100) of the thought with which the I tries to grasp him (or her[59]). This resistance that the Other expresses against the spontaneity of the I is not a violence. Rather, the putting into question of the I is "a welcome to the [Other]" (Levinas, 1996 p. 17) which "has a positive structure, ethical" (Levinas 1969, p. 197). Putting the I into question owes this positive structure to the fact that it does not entail the destruction of the I, but rather summons the enjoying I to respond to the challenge and command the Other makes "through his nakedness, through his destitution" (Levinas, 1996 p. 17) and through his (or her) hunger[60] (Levinas, 1998b p. 11). The I thus called into question becomes conscious of himself in responsibility, absolutely unique since "nobody can respond in its place" (Levinas, 1996 p. 18). As such, the conscious I is not responsible to the Other by choice or contract (Levinas 1981 p. 88). Rather, the conscious I is, "by its *very position*, responsibility

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58 I will not delve deeper into the intricacies of the phenomenology of the Other presenting itself, i.e., of the face. For a discussion of the face of the Other, see *Totality and Infinity*, section 3 (Levinas, 1969).

59 Levinas uses the *generic* 'he' when discussing the Other, thus technically not excluding those of other genders. Nevertheless, this is language that risks being discriminatory and would preferably be amended to reflect Levinas' own inclusionary intentions. However, simply including more genders (e.g., 'his or her' or 'his/her') would not be appropriate here, since speaking of the Other in terms of gender already constitutes a *grasping* of the infinite Other in terms of objectifying categories and, as such, fails to do justice to the Other's alterity. Regrettably, conventional gender-neutral alternatives are equally inappropriate for talking about the infinitely Other. That is, using the gender-neutral pronoun 'it' would amount to dehumanizing the Other, the use of a singular 'they' is incompatible with the uniqueness of the Other, and less commonly used singular gender-neutral pronouns still conjure up the problem of gender categorization. As such, I also revert to generic 'he', if only for textual consistency with the Levinasian source material. However, I have added 'or her' between brackets to disavow any intentional exclusion and to indicate the sometimes awkward struggle to find the best terms in which to describe the Other.

60 Levinas' focus on hunger stems from a somewhat grim analysis of modern sensitivity to the Other: "Of all the appetites [...] hunger is strangely sensitive in our secularized and technological world to the hunger of the other man. All our values are worn except this one. The hunger of the other awakens men from their sated drowsing and sobers them up from their self-sufficiency" (Levinas, 1998b p. 11).

through and through" (Levinas, 1996 p. 17, emphasis in the original). Responsibility, then, is the *leading experience* of the second stage: the egoistic spontaneity of the I is called into question by the infinitely Other, which positively establishes the conscious I as fundamentally responsible to the Other.

Just as this stage's leading experience involves putting into question the enjoyment of the I and its reorientation towards the Other as responsibility, its *objectivation regime* involves a disruption of possession and its reorientation towards the Other in the form of the *Gift*. This concrete articulation of responsibility in the form of the Gift is constituted by two instances of expression: dispossession of my possessions in conversation and their actual donation to the Other.

The first instance concerns the elementary response to the call of the Other, which lies in establishing a relationship with the Other in conversation. In conversation, I "*receive* from the Other beyond the capacity of the I", i.e., the Other *teaches* me by virtue of his (or her) infinite alterity (Levinas, 1969 p. 151). In turn, I speak to the Other of the world I possess (Levinas, 1969 p. 173). In so doing, the things of which I speak are put in common, receive a universality in language (Levinas, 1969 p. 76) that detaches them from the self-centered situatedness of possession and enjoyment. As such, the generalization that underlies language is an ethical event: it is "a primordial dispossession, a first donation" (Levinas, 1969 p. 173) which "permits me to render the things [of which I speak] offerable, detach them from my own usage, alienate them, render them exterior" (Levinas, 1969 p. 209)[61]. This allows for the second instance of the Gift: the actual donation of my possessions to the Other. As Levinas explains, responding to the Other is also a corporeal and substantial realization. It paralyzes enjoyment because it actually demands genuine sacrifice of myself and my possessions. That is, to respond to the Other's hunger and destitution involves "taking the bread out of my mouth, and making a gift of my own skin" (Levinas, 1981 p. 138), it is "the openness, not only of one's pocket book, but of the doors of one's home" (Levinas, 1981 p. 74). Through such sacrifice, the conscious I gives concrete form to its existence as responsible-for-the-Other.

To summarize, responsibility is this stage's leading experience, while its objectivation regime is formed by the Gift. Both responsibility and the Gift

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61 This explains Levinas' somewhat more cryptic statement of this relation: "in order that I be able to see things in themselves, that is, represent them to myself, refuse both enjoyment and possession, I *must know how to give* what I possess" (Levinas, 1969 p. 171, my emphasis).

signify a disruption and reorientation of the previous stage's leading experience and objectivation regime (i.e., enjoyment and possession) towards the Other. This positively produces an I that can speak for itself and is unique in its responsibility towards the Other. Responsibility signifies a relationship of radical asymmetry, it is a one-for-the-Other.

However, this relationship (i.e., ethics) is severely problematized with the arrival of a third party, another Other, "other than the neighbour but also another neighbour, and also a neighbour of the other, and not simply their fellow" (Levinas, 1996 p. 168). No longer can the I dedicate itself fully to the Other since the I is also responsible to the third party. A question now arises: "*What am I to do?*", and a decision must be made. Doing so is to engage the question of justice, which institutes the third stage.

3.2.3. Comparing Incomparables: Justice

The third stage, "Comparing Incomparables: Justice," imposes a dilemma onto the responsible 'I' since it positions the I in what one could call a properly social situation. That is, the I is no longer faced with just an Other, but with the Other and the third party: another Other, as unique as the first. What is the I to do now? How must it respond to them? This question redirects the I from its infinite responsibility for the Other to the primordial problem of justice (Levinas, 1981 p. 161), which inescapably requires the *comparison* of Others "in the very name of their dignity as unique and incomparable" (Levinas, Bouchetoux, and Jones, 2007 p. 206). And to compare them is to ask: "What [...] are the other and the third party with respect to one another?" (Levinas, 1996 p. 168). In other words, the problem posed by the third party cannot be engaged by simply respecting the Other's alterity, but requires determining what Levinas calls others' *quiddity* (Levinas, 1969 p. 177), i.e., asking *what* they are on top of respecting *who* they are. Only thus can the "comparison of incomparables" (Levinas, 1981 p. 158) required by justice be made. This in turn gives rise to a "search for a principle" (Levinas, 1981 p. 161) that includes "comparison, coexistence, contemporaneousness, assembling, order, thematization, the visibility of faces, [...] the intelligibility of a system, and thence also a copresence on an equal footing as before a court of justice" (Levinas, 1981 p. 157). Justice, thus described, constitutes the *leading experience* of the third stage. However, other than the leading experience in the previous two stages that had a straight-forward orientation (i.e., towards the I and the Other), the structure of justice is *dilem-*

matic. It pulls in two directions: the entrance of the third party introduces the problem of justice in the name of responsibility, yet any attempt at solving it necessarily falls short of the responsibility that motivates it because it cannot help but efface the others for which justice is required.

Having established justice as the third stage's leading experience, it is now possible to shine some light on its objectivation regime. For this, I take inspiration from the second stage where the objectivation regime underwent a parallel transformation to that of the leading experience (i.e., a reorientation from the I towards the Other). In the third stage, the transformation of the leading experience from responsibility to justice stems from the entrance of the third, which problematizes the I's singular and infinite responsibility towards the Other. The resulting problem of justice requires the consideration of others in terms of *what* they are, rendering them knowable, measurable, interchangeable, judgeable, which allows for the articulation and comparison of others' interests and needs. As such, the transformation of the leading experience in this stage revolves around opening up the possibility of *representation*. Its objectivation regime is likewise concerned with representation in two important ways: the representation of others in politics, and the representation of the world as 'ready to be given'.

First off, in responding to the problem of justice, consideration of the third party gives rise to "the We, aspires to a State, institutions, laws, which are the source of universality" (Levinas, 1969 p. 300), i.e., to *politics*. And it is through the institutions of politics that the comparison of others (and the I) is concretely established and their interests can be articulated and weighed against one another. As an objectivation of dilemmatic justice, however, politics also has a much more ominous side. Since politics also understands others in terms of 'what' they are (by their works and through their clothing) they are grasped as interchangeable objects (Levinas, 1989 p. 243-244). This constitutes a "great 'betrayal'" (Levinas, 1969 p. 44), as the objectivation of others obscures their otherness that ushered in the question of justice and politics in the first place. Politics, when left to its own devices, "judges them according to universal rules, and thus in absentia" (Levinas, 1969 p. 300). As a consequence, "the element of violence in the State, in the hierarchy, appears even when the hierarchy functions perfectly. [...] There are, if you like, the tears that a civil servant cannot see: the tears of the Other" (Levinas, 1996 p. 23). As such, politics unavoidably falls short of the responsibility that inspires it because it cannot help but efface the Other. This calls for an amendment to politics which "consists in making possible expression" (Levinas, 1969 p. 298) so that the others can call politics into question by demonstrating its blind spots and dangerous excesses. In other words, in the face of totalizing politics, "justice is a right to speak" (ibid.). In politics thus amended, which I call *just politics*, "the third and all those who, alongside the third are numerous humanity [can] remain to me as 'other', unique in its uniqueness, incomparable, and should concern me" (Levinas, Bouchetoux, and Jones, 2007 p. 206)[62]. Imperfect and incessantly called into question by others, politics presents a perpetual puzzle consisting of political and institutional systematization, deconstruction and modification.

This vision of politics provides a partial response to the problem of justice in that it makes possible the actual processes of comparing others and articulating and weighing their interests, all while leaving room for the Other to call politics into question. However, actually fulfilling the demands of justice also requires a parallel transformation of the concrete 'donation of my possessions' in the objectivation regime of the previous stage (the Gift). That is, the quiddity of the Other finds another concrete correlate in a way of knowing and representing the *world* that is no longer caught in the immediacy of my responsibility to a specific Other, but rather opens up the possibility of setting up that world as 'ready to be given', allowing it to be divided among numerous others in need.

However, Levinas' work does not clearly provide a theme that is straightforwardly fit for this position. Nonetheless, I would argue that such a way to set up the world as 'giftable' is probably best understood as *technology*. One finds support for this proposition in Levinas' (admittedly episodic) reflections on technology. In them, Levinas rejects Heidegger's negativity concerning modern technology[63] as he is unwilling to let go of the two main promises it holds for humanity. First, a wholesale condemnation of technology is, according to Levinas, "forgetful of the responsibilities to which a 'developing' humanity, more and more numerous, calls and which, without the development of technology, could not be fed" (Levinas, 1998b p. 9). In other words, through technology,

62 This quote originally concerns money and its redemptive qualities in preserving alterity amidst more totalizing systems. However, Levinas' positive assessment of this quality in such a systematized economic totality prompted me to include it as a goal in this discussion of politics.

63 Levinas' reflections on technology were mainly made in reply to Heidegger's analysis in his famous essay "The Question Concerning Technology" (Heidegger, 1977), although other Heideggerian themes are also caught in the crossfire, notably his focus on Place and enrootedness.

humanity is supremely able to transform the world into nourishment, into matter that can be enjoyed[64]. These products of technology are separated from the responsibility to a specific Other and can thus be gifted to those numerous others that need it, thus providing politics with the 'raw materials' it needs to fulfil its responsibilities. Secondly, technology is secularizing. It teaches us that worship of the world, be it in terms of nature, blood or place, only serves to obscure the alterity and uniqueness of the Other. Technology shows us that these 'gods' are "of the world, and therefore are things, and being things they are nothing much" (Levinas, 2000 p. 166). Leaving behind such idolatries, an opportunity arises by virtue of secularizing technology: "to perceive men outside the situation in which they are placed, and let the human face shine in all its nudity" (Levinas, 1990 p. 233). In other words, technology is conducive of a just politics in which the Other can call both politics and technology into question[65].

Like politics, however, technology poses a number of dangers, especially when left to its own devices. First, technical things can be actually dangerous. Not only can they pollute "the air we breathe" (Levinas, 1998b p.9), but they even "risk blowing up the planet" (Levinas, 1990 p. 231). Secondly, technology "threaten[s] a person's identity" (Levinas, 1990 p. 231). That is, in a technological society, the Other risks becoming little more than a cog in a larger technological machinery[66]. Whether others are considered as simply "desiring machines" (Levinas, 1989 p. 240) or mere capital in the workings of capitalism (Levinas, 2003 p. 50), their technological objectification could lead to their enslavement: "in a totally industrialized society [which is the result] of supposedly perfected social techniques – the rights of man are compromised by the very practices for which they supplied the motivation" (Levinas, 1993 p. 121).

Thus arises another parallel between technology and politics: both are motivated by our responsibility to others, yet both threaten that very motivation by virtue of their essential *modi operandi*. For politics, the solution was to open it

64 While this may sound familiar to Heidegger's 'enframing' the world as 'standing reserve' (Heidegger, 1977), its ethical implications are vastly different.

65 Levinas even goes so far as to say that "[s]cience and the possibilities of technology are the first conditions for the factual implementation of the respect for the rights of man" (Levinas, 1993 p. 119).

66 This is the most important point that Levinas grants to Heidegger's analysis of humanity's fate in a modern technological world (Heidegger, 1977), although he does not agree with Heidegger concerning its inevitability.

up to the questioning of the Other, thus laying the foundation for a perpetually puzzling just politics. Conversely, technology is to be *subordinated* to such a just politics[67], since "giving precedence to politics over physics is to work for a better world, to believe the world to be transformable *and* human" (Levinas, 1994 p. 143, my emphasis)[68] for several reasons. First, subordinating technology to a politics that is inspired and interrupted by responsibility is to align the specific technological set-up of the world with the needs of justice. Secondly, a just political process allows the Other to call into question (aspects of) both political and technological systems, thus avoiding the totalizing and objectifying excesses to which they are prone. This means that, like politics, technology is bound to be ever-changing: inspired by just politics, our technological set-up of the world is constantly in question and in need of improvement.

In sum, the entrance of the third party problematizes both the singular responsibility towards the Other and the Gift, evoking politics and technology, respectively, in order to tackle the problem of justice. However, both politics and technology have a dilemmatic structure *vis-à-vis* the responsibility that animates them. On the one hand, politics allows for the comparison of incomparable others and the responsibilities towards them and technology sets up the world as giftable and secularized. On the other hand, politics and technology tend towards dangerous excesses. The remedy for these excesses lies in 1) welcoming the Other calling politics into question, thus forming the just politics that is the first way in which justice is 'objectivated', and 2) the subordination of the second objectivation of justice, i.e., technology, to just politics and the questioning Other. This specific constellation of just politics and subordinated technology are hereafter referred to as Levinasian *techno-politics,* a term I introduce here to highlight both technology and politics' importance for justice. In the end, it follows from all this that Levinasian techno-politics is never final, always falling short of the responsibility that motivates it and thus incessantly in need of the improvements called for by others.

67 This is not always easy. Levinas demonstrates this with the example of the atomic bomb, the potential impact of which was so vast that it clouded any politics that was to take place in its threatening presence (Levinas, 1994).

68 My translation from the original French: "Donner le pas à la politique sur la physique est une invite à oeuvrer pour un monde meilleur, à croire le monde transformable et humain".

3.3. Locating Innovation in Levinas and Relating it to Responsibility

Having discussed all three stages, it is now clear where responsibility (i.e., as the leading experience of the second stage) is located in relation to other themes in Levinas' work, including egoism, possession, justice, politics, and technology. However, the analysis has not yet located innovation. If, however, innovation can be broadly construed as "the process of bringing something new into the world, through a combination of intellectual and practical ingenuity" (Grinbaum and Groves, 2013 p. 119), then only one stage stands out as a possible location for innovation: the third stage, 'Comparing Incomparables: Justice'. First, only in this stage are the world and the others that live in it represented in such a way that they can become part of intellectual or practical projects towards novelty. Moreover, a perpetual need for novelty is ingrained into Levinasian techno-politics if it is to do honour to the responsibility that inspires it. That is, in light of techno-politics' objectification and effacing of others, it is necessary to welcome the questioning Other and incessantly deconstruct, improve and reinvent current techno-political constellations. This process is where innovation takes place within the Levinasian framework presented above. Consequently, innovation is an inescapable part of a Levinasian techno-politics.

Having located responsibility in the second stage as its leading experience, and innovation in the need for novelty in the third stage, it is now possible to flesh out the relation between the two notions more thoroughly. From the analysis above, three ways in which responsibility and innovation are related can be deduced: one foundational, one ethical, and one structural.

The first way in which responsibility is related to innovation is foundational. Since responsibility is metaphysically prior to innovation, it is a precondition for it. That is, innovation is the means of adjustment and improvement of techno-politics, and techno-politics only arises after the problematization of the second stage's leading experience (i.e., responsibility) by the entrance of the third party. In other words, innovation is always already grounded in responsibility[69]. The second way responsibility relates to innovation is ethical. Initially, our responsi-

69 It is important to note that there is a positive role for *enjoyment* in innovation too. For example, enjoyment underlies the activities of the engineer who (inspired by the needs of others) thinks, reads, works and uses tools to innovate (as described in 'Origins of the I: Egoism', above; see Florman, 2013). So, while the structure of the experience of enjoyment is self-centred, activities that are enjoyed may nevertheless lead to outcomes that can nourish the Other and aid the cause of justice if they are ultimately motivated by responsibility.

bilities towards the Other and the third party (including the dilemmas those responsibilities pose) are the ethical driving force behind the development of technology and politics. As such, responsibility motivates the development of that which can be innovated in the first place. More importantly, however, it is the responsibility towards the Other who puts into question techno-politics that necessitates innovation and determines its direction. In other words, innovation is a response to responsibility. Finally, responsibility and innovation are related structurally, i.e., in terms of how the outcomes of innovation form the structures through which we can actually work towards justice. Given that the outcomes of innovation consist of new political and technological means aimed at overcoming the dangers, omissions and excesses of current techno-political systems, innovation actively works towards justice by shaping and reshaping the structures and resources necessary to fulfil our responsibilities towards others.

In sum, responsibility is not only a metaphysical precondition for both technology and politics (that which is to be innovated) but, more importantly, it demands their creation as well as their innovation, which in turn provides (presumably) more and (ideally) better technological and political structures through which to fulfil our responsibilities. As such, innovation should first and foremost be a response to responsibility; a response that is always provisional given the dilemmatic structure of techno-politics. In the next section, thinking of innovation in this way is shown to help overcome at least some of the problems associated with the 'regular' notion of innovation.

3.4. Levinas, Responsibility and Innovation: Implications and Corroboration for RI

Locating both responsibility and innovation in Levinas' philosophy established their relation as foundational, ethical and structural. While this does not provide fully conceptualized and formalized notions of either term, some implications for RI can still be induced.

One primary implication is that the relation between the 'responsible' and 'innovation' parts of RI should not be read, either philosophically or practically, in terms of addition. Responsibility is not something to be added onto innovation (cf. Blok and Lemmens 2015). Rather, it is built into the very experiential structure of innovation (as its foundation and motivation), and should be built into the very process of innovation too (to work towards outcomes that substantially contribute to addressing the problem of justice).

In what follows, other implications are explored by contrasting aspects of 'Levinasian' innovation that is explicitly founded on and motivated by responsibility with some of the possible pitfalls associated with innovation that does not explicitly aim to be responsible, understood here as 'regular' innovation[70](Blok & Lemmens, 2015)[71]. Not only can these pitfalls be avoided by innovation that is related to responsibility as described above, but the Levinasian framework and its implications for RI are shown to be compatible with and to provide additional moral grounding for some features of RI that are already present in the literature.

The first pitfall one risks walking into is a disproportionate amount of attention for *technological* innovation. As the nature of a Levinasian techno-politics shows, however, responsibility calls for innovation in politics as well as in technology. This is compatible with calls by a number of RI scholars for value-sensitive institutional redesign (Correljé et al., 2015; Taebi et al., 2014) or institutional reflexivity, learning and development (Macnaghten et al., 2014; Owen et al., 2013). On top of this, however, Levinasian techno-politics dictates that in RI, technological innovation should be subject to just politics if it is to operate in service of justice and the responsibility by which it is inspired.

The second possible pitfall is that innovation may become seen as *inherently good*. That is, innovations are meant to solve known societal problems and supposedly deliver prosperity and employment (von Schomberg, 2013). On the one hand, the introduction of innovations simultaneously implies the destruction of some other established capital, institutions and practices (Blok & Lemmens, 2015; Schumpeter, 1942), which would seem to forfeit innovation's status as inherently good. On the other hand, according to the analysis above, this destruction can actually be part of what motivates innovation in the first place. Arguably, the aspects of techno-politics put into question by the Other might actually have to be 'destroyed', replaced or improved. Even so, innovations are always only provisional responses to the Other's scrutiny because they

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70 It should be noted that, if the Levinasian analysis is correct, responsibility is also a precondition for 'regular' innovation, and can be a motivation for it. Still, it can be said that there is a considerably less developed role for responsibility in the techno-politics of 'regular' innovation.

71 Blok and Lemmens (2015) do not present their analysis in terms of possible pitfalls, but describe a concept of innovation that is purportedly "self-evidently presupposed" in the RI literature (p. 28). As this section shows, however, the RI literature already describes characteristics of innovation that are at odds with their notion of 'regular' innovation.

necessarily fall short of the responsibility that inspires them (see section 2.3). It is in light of its metaphysical foundations, then, that innovation simply cannot be inherently good. This openness to the Other's questioning has three further implications for RI. First, it should welcome critical others and allow them influence concerning the focus and direction of innovation. This provides support for some features of RI that have long been recognized: that it should be deliberative (Owen et al., 2013) and that those potentially influenced by the innovations should be informed about them and be able to "influence the setting up, carrying out, monitoring, evaluating, adapting, and stopping" of their implementation (van de Poel, 2016 p. 680). Secondly, RI should be self-critical and reflective (Owen et al., 2013) and produce institutional and technological innovations that are responsive to the need for future change or adaptation (ibid.) and flexible so that their further implementation could be stopped and their negative impacts reversed or compensated (Bergen, 2016b; van de Poel, 2016). However, since systematization is still necessary for techno-politics to be effective (i.e., to be able to work towards justice), such flexibility will inevitably be limited (Bergen, 2016a). Thirdly, all this means that the outcomes of RI are never final, and that RI is a perpetual process towards an inclusive techno-politics.

The third pitfall associated with 'regular' innovation is that economic feasibility could be seen as a necessary condition for its success. The analysis presented in this paper does not necessarily eschew economic considerations. After all, a focus on economic success can be understood from the point of view of techno-political necessity. The aggregation and weighing of needs and interests fits in the *modus operandi* of techno-politics without which "humanity [...] could not be fed" (Levinas 1998b, p. 9). Notwithstanding this potential, the very economic calculations that enable justice also risk effacing those others in service of which they work. Economic parameters must not obscure the real responsibilities to which RI is a response. This is in line with similar reservations already present in the RI literature. For one, innovation should primarily serve those others who need it most (Soete, 2013). Along similar lines, innovating responsibly requires attention for the just distribution of potential hazards and benefits as well as protection of those that are most vulnerable (van de Poel, 2016).

Lastly, 'regular' innovation risks being blind to the asymmetries in knowledge and power between actors involved in or affected by innovation(s) (Blok &

Lemmens, 2015; Stirling, 2008; van Oudheusden, 2014)[72]. However, the relation between responsibility and innovation provides a counterweight to such asymmetries, which can be said to arise in the third stage where both knowledge as well as power over others becomes possible through techno-politics. As in techno-politics generally, the counterweight to power asymmetries in RI lies in the asymmetry inherent in the responsibility of the I towards the Other. That is, the Other calling the I to responsibility defies and resists the I's ability for power to achieve its egoistic goals. It does so without needing power itself, because the way the Other presents itself is "not a force. It is an authority. Authority is often without force"(Levinas, 1988 p. 169)[73]. The authority of the Other's ethical demand is a counterweight to power not because it is more powerful but because it puts into question the very right to that power and that which is to be achieved by it. However, this 'ethical' asymmetry is at odds with aspirations towards symmetrical 'mutual responsiveness' between stakeholders that currently underlies a lot of work on RI. Blok (2014) has nonetheless taken up the task of harnessing the potential of ethical asymmetry through the concept of dialogical responsiveness between RI stakeholders. Such dialogical responsiveness focuses on the very act of dialogue between stakeholders in which they would become critical towards themselves and where their identity is dialogically constituted and deconstructed. Such a model of stakeholder dialogue could help in living up to the ethical and structural relation between responsibility and innovation.

3.5. Conclusion

In order to contribute to a better understanding of RI, this paper shed light on the relation between responsibility and innovation and sketched some of its implications for RI.

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72 Blok and Lemmens (2015) argue that RI presupposes symmetry between actors in the way it attempts to include ethics in the innovation process, judging this specific assumption to be naïve. To me, this presupposes more conceptual content than their 'regular' notion of innovation contains, which I would rather attribute to the specific participatory interpretation of the 'responsible' part of RI. The regular notion of innovation has little to nothing to say about actor symmetry, hence my formulation of the fourth pitfall in terms of a blindness of asymmetries rather than the presupposition of symmetry.

73 See footnote 59.

To this end, both responsibility and innovation were located within the ethical phenomenology of Emmanuel Levinas, which was structured into three stages for the purposes of this paper. Each stage was discussed in terms of its 'leading experience' and 'objectivation regime'. Whereas the first stage is driven by enjoyment that becomes objectivated in the form of possession, the second stage disrupts this enjoyment and reorients the ego towards responsibility towards the Other. This responsibility becomes objectivated as the Gift, the dispossession of my possessions and their donation to the Other. With the entrance of the third party to which the I is also responsible, the third stage ushers in the problem of justice. Tackling this problem calls for the establishment of a Levinasian techno-politics. However, given the totalizing tendencies of such a techno-politics, it is vital to welcome the Other who questions techno-politics and identifies its blind spots and dangerous excesses. In so doing, the Other calls us to responsibility to change techno-politics for the better, i.e., to innovate.

It was concluded that innovation and responsibility are intrinsically related in at least three important ways. First, they are related foundationally because responsibility is metaphysically prior to innovation and as such, a precondition for it. Secondly, they are related ethically since innovation is driven by responsibility, i.e., by the Other calling on us to innovate for the better. Lastly, they are related structurally in the sense that the outcomes of innovation form the structures through which we can actually attempt to fulfil our responsibilities to others. Conceptualizing the relation between responsibility and innovation in this fashion establishes innovation as a response to responsibility, albeit one that should be seen as provisional and open to future innovation.

Rethinking the relation between responsibility and innovation in this way has a number of implications for RI. First and foremost, it means that responsibility cannot simply be added to innovation. It is already built into the experience of innovation and should also be an integral part of the process of innovation. Secondly, the Levinasian analysis confirms the need for both technological as well as political/institutional innovation in RI. Thirdly, the framework presented in this paper enriches our conception of the normative status of innovation in RI. That is, while innovation is motivated by and necessary in light of responsibility, it is also inevitably provisional, and falls short of the responsibility that inspired it. On top of this, innovation's roots in responsibility and justice make it cautious of measuring RI's success in purely economic terms. Lastly, the authority of the Other calling innovators to responsibility can provide a counterweight to power asymmetries in RI processes. These implications resonate rather well with a number of more specific proposals in recent scholarship on innovating responsibly. These include calls for protection and prioritization of those most vulnerable, flexibility or responsiveness of the innovation process as well as its outcomes, and the need for deliberative and critical engagement of stakeholders so as to improve and provide direction to innovation. As such, the relation between responsibility and innovation provides moral grounding for such proposals for RI.

4 Path Dependence, Agency and the Phenomenology of Technology Adoption

The theory of path dependence remains a popular explanation for why markets or societies become locked into specific technological trajectories that become increasingly inflexible over time. However, a number of scholars have become skeptical of the value of historical case studies for studying path dependence (the dominant method up to this point) and instead recommend other approaches like lab experiments and simulations. Nonetheless, the 'thick' description of actual cases may still have significant value for the study of technological path dependence. First, thick socio-technical descriptions of the environment in which technology adoption occurs reveals normatively problematic aspects of path dependence beyond inefficiency. Secondly, a thicker, structurational notion of agency in path dependent processes could help to alleviate concerns about path dependence' allegedly excessive determinism and its reliance on contingency for path creation. This paper aims to contribute to such a structurational notion of agency by developing conceptual resources for agent-centred descriptions of technological path dependence. It does so by reinterpreting the basic evolutionary building blocks of path dependence (i.e., technology adoption, technology and the social selection environment) through the lens of Alfred Schutz' social phenomenology. The resulting perspectives provide a number of conceptual resources that should allow for better describing why and how agents make the technology adoption decisions that they do, and the way in which technology and the social selection environment mediate those choices and their consequences.

4.1. Introduction

Some technologies that were introduced in the past no longer seem as attractive as they once did. Usually, a switch to alternative solutions does not present practically insurmountable difficulties. This is, however, not always the case. For some technologies -whether relatively simple ones like the QWERTY keyboard or large technological infrastructures like fossil-fuel based transport systems or those related to nuclear energy- it may prove incredibly difficult to reverse their dominance even when there are good reasons to do so (Bergen, 2016b; Cowan, 1990; David, 1985; Foxon & Pearson, 2008). In such a situation, the technology in question can be called locked-in. If we are to avoid becoming locked into such a potentially less-than-ideal technological trajectory, it is of course important to understand how such a situation comes about. One approach explaining the lock-in phenomenon can be found in the concept of *path dependence*, in which self-reinforcing sequences of technology adoption lead to inflexible market outcomes.

The concept of path dependence has seen widespread application across the social sciences in the past few decades, examining a wide range of topics such as the lock-in of technologies (Bergen, 2016b; Cowan, 1990; W. Walker, 2000), regional economic development (Martin & Sunley, 2010) and institutions both inside the firm (David, 1994; Vergne & Durand, 2011) and beyond (North, 1990). This application has, however, also seen great variation in the extent to which path dependence was formalized as a specific theory of technological or institutional persistence. Indeed, it has at times been used as a "trendy, catch-all phrase to describe virtually every sequence of events where history seems to matter on the surface" (Vergne, 2013 p. 1194). Such broad application has made path dependence subject to the risk of concept stretching and proliferation, thus limiting its specificity and explanatory potential (Rixen & Viola, 2014). To avoid this, a lot of work theoretical work on path dependence has involved specifying the basic structure of path dependent processes (e.g., Arthur, 1989, 1994; Martin & Sunley, 2010; Sydow, Schreyögg, & Koch, 2009), identifying specific mechanisms that drive path dependent processes (Arthur, 1994; David, 1985, 1994; Dobusch & Schüßler, 2013; Mahoney, 2000; Page, 2006; W. Walker, 2000), delineating path dependence from other types of explanations for technological or institutional persistence (e.g., Rixen & Viola, 2014; Sydow et al., 2009; Vergne & Durand, 2010), prescribing more rigorous methods for path dependence studies (e.g., Vergne & Durand, 2010, 2011), and qualifying the normatively problematic aspects of path dependence (e.g., Liebowitz & Margolis, 1995).

This paper aims to contribute to path dependence' further theoretical development by elaborating on an arguably underdeveloped but promising strand of the path dependence literature. Specifically, it is concerned with the further development of a 'thick' notion of agency that could help to alleviate some of path dependence' problematic aspects without losing the theoretical specificity developed in the abovementioned efforts. Section 4.2 provides a succinct overview of the basic tenets of path dependence, criticisms levelled against it, and the potential advantages that a thick notion of agency could bring to the table.

4.2. Path Dependence: Basics, Criticisms, and the Importance of Thick Descriptions

To start, I take the following to generally describe the basic structure of a path dependent process by which a technology becomes locked-in[74] (Arthur, 1989, 1994; Sydow et al., 2009):

1. The *Preformation Phase*. This phase is characterized by a broad scope of action for agents since multiple technological alternatives are available to them. However, significant uncertainty usually exists concerning the technologies' performance, payoffs, the future rate of adoption by others and/or eventual market outcomes. Indeed, in this stage it is impossible to predict *ex-ante* which technology will gain the upper hand or which will end up being the "best" option available (e.g., because that may depend on the number of other adopters). However, once a specific technology gains a small but significant lead over competing technologies, this may constitute a 'small historical event' that sets history off on a specific new path[75] if these events set off a self-reinforcing process. This also constitutes the end of the preformation phase.
2. The *Formation Phase*. The formation phase is characterized by processes of self-reinforcement that tend to amplify a technology's initial lead. That is, adoption of the leading technology increases the chance that that technology will be adopted in the future[76], while alternatives become increasingly unattractive in comparison. As such, while different outcome

74 There is still significant variation among path dependence studies when it comes to this description, if not in structure then in emphasis on the relative importance of specific phases.

75 Such small historical events have also been called 'random' because they are situated beneath the resolution of the analyst's lens (Arthur, 1990), because these decisions were not made with the optimality of the system which would result from these decisions in mind (David, 2007), or simply because they were not clearly predictable by the theoretical models usually employed to understand the system at hand (Mahoney, 2000).

76 That is, $p_{adoption}(Tech)_{t+1} > p_{adoption}(Tech)_1$ due to self-reinforcement. Note that this implies *endogeneity* of path reinforcement (Rixen & Viola, 2014).

distributions are still possible, the range of options narrows over time as self-reinforcement continues.

Different mechanisms have been identified as contributing to self-reinforcement in the formation phase. Historically, the literature has reserved most of its attention for positive feedback mechanisms based on *increasing returns* to technology adoption. Such mechanisms include large set-up costs and economies of scale (Arthur, 1990; David, 1985), positive network externalities (Katz & Shapiro, 1985), adaptive (possibly self-fulfilling) expectations (Arthur, 1994; Dobusch & Schüßler, 2013), technology-specific learning effects, including learning-by-doing and learning-about-payoffs (Cowan, 1990), interrelatedness and compatibility with other technologies (David, 1985; Dobusch & Schüßler, 2013), and the cumulative nature of quasi-irreversible investments in terms of capital, infrastructure, contracts, etc. (David, 1985, 2007; W. Walker, 2000). However, in addition to positive mechanisms reinforcing the dominant path, some authors have also highlighted the importance of *negative mechanisms* that decrease the likelihood of other paths being selected (Vergne & Durand, 2011), with negative externalities being considered necessary for path dependence to occur (Page, 2006).

As these mechanisms help to further reinforce the dominant path, the outcome distribution further narrows to such an extent that "the dominant decision pattern becomes fixed and gains a deterministic character" (Sydow et al., 2009 p. 692). At this point, the process enters the third phase.

3. The *Lock-in Phase*. In this, the dominance of the selected technology is said to be irreversible. However, it is important to note that lock-in implies a relatively weak notion of irreversibility (Perrings & Brock, 2009). Not only is this dominance *in principle* reversible (although practically highly unlikely), but it usually also temporary. That is, the locked-in system is susceptible to exogenous shock, opening up possibilities for technological alternatives. As such, lock-in is probably better understood in terms of 'inflexibility' (Arthur, 1994) or 'contingent irreversibility' (Desjardins, 2013).

   Still, this situation is seen as potentially problematic since there is no guarantee that the best or most efficient technology comes to dominate the market under conditions of self-reinforcement (Arthur, 1989)[77]. As such, the emergence of lock-in bears a risk of potential inefficiency.

It is important to note, however, that while lock-in is a system property, it is an emergent one. That is, through mechanisms of self-reinforcement, individual technology adoption decisions give rise to system-level inflexibility (Cantner & Vannuccini, 2016)[78]. In this, one recognizes the basic (quasi-)evolutionary model underlying path dependence (Cecere, Corrocher, Gossart, & Ozman, 2014; Desjardins, 2013; Dobusch & Schüßler, 2013; Perrings & Brock, 2009)[79]: individual *technology adoption* decisions by agents (selection) among different *technological alternatives* (variation) within a specific socio-technical *selection environment* increase the likelihood of reinforcing the dominance of the technology that gained a lead in the preformation phase. As such, technology, its adoption and the environment in which that occurs are taken to be the basic *evolutionary building blocks* of path dependence.

This, then, I take to be a general description of the basic structure of technological path dependence and lock-in, which, at least to some extent, has been at the core of path dependence studies. Despite path dependence' popularity, however, a number of important criticisms concerning it has been formulated over the years, three of which are discussed here: the focus on inefficiency, excessive determinism, and the necessity of contingency.

First, some of lock-in's normative implications have often been overstated (Kay, 2005). More specifically, while Arthur (1994) originally surmised that inefficiency is only a *potential* attribute of lock-in, fear of market failure has

77 Of course, what exactly makes a technology the 'best' or 'most efficient' one is not set in stone and consensus concerning these valuations may well be absent. For the basic structure of path dependent processes, however, this is of lesser importance.

78 In other words, to be compelling, path dependence must be able "identify and elucidate the role of critical human actions (or failures to act) that are shaped by transient and incidental circumstances – conditions which were not obviously pertinent to the principal issues of interest in the drama, yet from whose influence a succession of unanticipated and ultimately unwanted results unfolded" (David, 2007 p. 95).

79 As some of the 'founding fathers' of path dependence theory note, the dynamics of path dependence have an "evolutionary flavor, with a 'founder effect' mechanism akin to that in genetics" (Arthur, 1994 p. 28), causing institutions and technologies to " 'evolve' in a manner that shares important attributes with biological processes of evolution" (David, 1994 p. 217).

nevertheless animated much of the literature on technological path dependence (Liebowitz & Margolis, 1995; Vergne & Durand, 2011). However, in most cases of path dependence and lock-in, inefficiency is not an issue and when it is, it usually does not imply market failure (Liebowitz & Margolis, 1995)[80]. Even so, path dependence deserves our attention. For one, it can still be analytically valuable in understanding historical processes of social evolution and persistence (Pierson, 2000). Moreover, from a "strategic, future-oriented point of view," retaining flexibility by avoiding lock-in may have significant strategic value (Sydow et al., 2009 p. 695). For example, uncertainty about the future is not limited to payoffs or market outcomes. Other morally relevant aspects of a technology only become clear when the technology is already implemented on a sufficiently large scale, including risks (van de Poel, 2016) and specific institutional structures connected to the technology (Bergen, 2016a).

A second line of criticism focuses on path dependence' allegedly excessive determinism (Kay, 2005). Indeed, the basic structure leaves very little room for endogenous change once a system is locked-in because as long as self-reinforcement holds, maximizing agents[81] endogenous to the system would simply continue to reinforce the dominant technology. This conception of path dependent processes leaves little to no room for the possibility of endogenous innovation and creativity as ways of weakening a dominant path (Martin & Sunley, 2010).

A third criticism of path dependence involves the preformation phase. While some authors do not see this phase as essential for path dependence (e.g., Dobusch & Schüßler, 2013), others contend that the condition of contingency can be analytically problematic. That is, if contingency is essential for path dependence, it implies that things could have been otherwise. Using historical case studies (the historically dominant method in path dependence research), such a counterfactual is difficult if not impossible to retroactively prove. As such,

80 That is, most cases involve first- and/or second-degree path dependence. According to Liebowitz and Margolis (1995), only third-degree path dependence (where inefficiency is present and was remediable) is problematic. Additionally, revisiting important case studies such as QWERTY's lock-in (David, 1985) has shown that inefficiency has at times too easily been assumed to be both present and problematic (Kay, 2013; Liebowitz & Margolis, 1990).

81 Such models often assume rational or boundedly-rational models of agency (e.g., Arthur, 1989, 1994). While this is in accord with a normative focus on pareto (in)efficiency, novel decision-theoretical models could very well be needed for modelling path dependence (Page, 2006).

some scholars call for different research methods that would allow for dealing with this problem, such as lab experiments, simulations and counterfactual analysis (Vergne & Durand, 2010, 2011)[82]. However, to then also eliminate historical case studies from our repertoire of research methods for path dependent processes would arguably amount to throwing the baby out with the bathwater.

Indeed, 'thick'[83] socio-technical description of cases can still provide a number of distinct advantages for path dependence studies that aim at policy relevance (Cantner & Vannuccini, 2016), even if such methods do not provide great predictive capabilities (Kay, 2005; Page, 2006). Moreover, they can actually help to alleviate some of the concerns raised in the three criticisms mentioned above.
For one, thick descriptions of the *environment* in which agents make their technology adoption decisions are compatible with normatively problematic aspects of path dependence other than inefficiency because they often point beyond only utilitarian or market considerations. Indeed, policy, political, normative and symbolic factors also have a profound influence on (and are influenced by) technology selection (Cecere et al., 2014; Sydow et al., 2009). For path dependence, this means that self-reinforcement may be driven by mechanisms that are not based mainly on economic or utilitarian considerations (as in many archetypal cases), but rather on considerations of functionality in larger systems, a technology's legitimacy or power discrepancies between social groups. As such, there are *utilitarian* as well as *functional, legitimacy* and *power* explanations for path reinforcement (Mahoney, 2000)[84]. Such additional explanations

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82 Research applying these methods remains relatively scarce for now (e.g., Hossain & Morgan, 2009).

83 The notion of 'thick description' in this chapter does not refer to the anthropological methodology of the same name popularized by Geertz (1973). Rather, the notion of 'thick' descriptions simply denotes their aim to provide a more nuanced understanding of both the context and the underlying structures of the phenomena described (i.e. of agency in a socio-technical environment) without interpreting them in an overly reductionist or mechanistic fashion (as one would in some economic models).

84 While Mahoney discusses the different explanations for path dependence in terms of *institutional* reproduction, it nevertheless makes sense that similar types of mechanisms are capable of driving *technological* path dependence. Also, Mahoney talks about 'legitimation explanations' rather than 'legitimacy explanations'. However, in light of the discussion in section 4.7, 'legitimation' seems to imply active processes of legitimation, which would fall under power explanations according to the theory developed in this paper.

are undoubtedly relevant for at least some technology policy, e.g., for technologies of significant symbolic and political significance such as nuclear energy (e.g., Lawrence, Sovacool, & Stirling, 2016) or for technologies with normatively regrettable downsides not appropriately reflected in the market, such as those standing in the way of eco-innovations (Cecere et al., 2014). In so doing, thick descriptions of the technology selection environment point beyond inefficiency as the most important normatively problematic implication of path dependence. I.e., functional, legitimacy and power explanations bring with them their own potential problematic aspects, such as specific political power structures[85] or widespread legitimation and normalization of technology-related behaviours that are regrettable for reasons other than inefficiency.

Similarly, it stands to reason that thick descriptions of *agency* in path dependent processes could be equally fruitful. For example, thick descriptions of agency, including how agents navigate and act upon their world and the choices with which they are faced, could partially mitigate the second and third criticism.

More specifically, some have highlighted the need for more pro-active, strategic, and creative notions of agency for path dependence studies (Araujo & Harrison, 2002; Garud, Kumaraswamy & Karnøe, 2010) that would allow for "understanding path dependence not simply from a retrospective perspective but also from an actor-centred standpoint, focusing on how actors react to an uncertain future in real time" (Araujo & Harrison, 2002 p. 5). This opens up possibilities for endogenous change by allowing for a) the possibility that a path gets created by strategic action by actors, thus alleviating worries about the necessity of 'contingent' events, and b) the possibility of endogenously innovating out of lock-in instead of having to rely on exogenous shock for weakening a dominant path, thus relaxing the problem of excessive determinism (Martin & Sunley, 2010). As such, they soften some of path dependence' problematic aspects, and broaden both the scope and outcome possibilities for path dependence studies without thereby necessarily losing much of path dependence' theoretical specificity or definitional clarity.

Some steps have already been taken towards such notions of agency, most of which take an appropriate account of agency to be 'structurational' in nature (e.g., Araujo & Harrison, 2002; Garud, Kumaraswamy & Karnøe, 2010; Sydow

85 The political implications of nuclear power are a case in point (Winner, 1980).

et al., 2009)[86]. That is, agency and individual choices and actions cannot be understood outside of the socio-technical context in which they occur (i.e., the environment), and neither is it possible to make sense of (the evolution of) that context without agency. On such an account, agents are *iterational* (referring to the recurring use of routine ways of dealing with situations), *projective* (referring to an imaginative future-orientedness in terms of scenario's for action with regard to one's interests, desires, etc.) and practical- evaluative (referring to the capacity to make normative and practical judgements)(Araujo & Harrison, 2002 p. 8).

In this paper, I continue along this path towards thick, structurational descriptions of agency in studies of technological path dependence by further developing some of the conceptual resources needed for such descriptions. Such resources must at least a) incorporate the three above-mentioned characteristics of structurational agency, b) centre around on what drives path self-reinforcement, i.e., they must have something to say on how technology can be adopted, c) highlight the interconnectedness of agency with the structures in which it is exercised, and d) should be at least nominally compatible with utilitarian, functional, legitimacy and power explanations of path reinforcement.

This is achieved by reinterpreting the basic evolutionary building blocks of technological path dependence presented above (technology, technology adoption, and the environment in which it occurs) in terms of Alfred Schutz' social phenomenology. Such a phenomenological foundation anchors these reinterpretations in agents' experience of the world in which they live and which they navigate. Additionally, since Schutz focused on the development of an explicitly *social* phenomenology, it facilitates the connection between agent-centred phenomenological insights with their social (and technological) implications (Dreher, 2011).

Section 4.4 provides a Schutzian exploration of the subjective process of choosing and acting. This results in a broad perspective on technology adoption that incorporates the characteristics of structurational agency. Subsequently, sections 4.5 and 4.6 describe technology and the social selection environment in a way that highlights the interconnectedness of agency to structure and provides

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86 'Structurational' means that this notion of agency is in accordance with Giddens' conception of the duality of structure and agency (Giddens, 1984).

further resources for the analysis in Section 4.7, where insights from the previous sections are mapped onto the different kinds of explanations of path self-reinforcement that reflect a thick understanding of the context in which technology adoption occurs. Before all this, however, Section 4.3 provides a short introduction to some of the relevant tenets of Schutz' work and thus presents some essential theoretical background for sections 4.4, 4.5 and 4.6.

4.3. Some Basic Insights into the Structure of Everyday Experience

Schutz set out to provide a comprehensive phenomenological analysis of something rather mundane: our experience of the everyday life-world. This life-world is the "province of reality which the wide-awake and normal adult simply takes for granted in the attitude of common sense" (Schutz & Luckmann 1973 pp. 3-4), its objects self-evidently real and unproblematic. These include my consociates[87] with whom this pre-given social and cultural life-world is essentially shared[88]. Three important elements that shape the subjective experience of the life-world are briefly discussed below: the subjective stock of knowledge, its systems of relevance, and its objectivations in the outer world.

The way in which I experience the life-world is first of all dependent on what I know of that world or what I expect from my actions upon it, i.e., on the form and content of my *subjective stock of knowledge*. This subjective stock of knowledge broadly consists of three 'types' of elements: fundamental, habitual, and specific (Schutz & Luckmann 1973).

The *fundamental* elements of the subjective stock of knowledge concern the basic boundaries of the situation in which I find myself, and are more or less automatically given in the horizon of each experience. For example, my situation usually includes (a) socially objectified system(s) of basic typifications, such as those found in common language. The *habitual* elements of the subjective stock of knowledge concern routine mastery of familiar problems I encounter. These routine elements include skills (e.g. walking), useful knowledge (e.g., how to

87 Although it was not used as frequently by Schutz, I prefer the term 'consociates' (or simply 'others') to 'fellow-men' given the risk of exclusion inherent in the latter.

88 The fact that the life-world is shared allows for intersubjective communication, coordination and cooperation, which in turn can influence the life-world. Unsurprisingly, then, the current structure of the life-world is the product of innumerable interactions between ancestors.

write), and knowledge of recipes (e.g., how to get coffee from the faculty coffee machine). The *specific* elements of the stock of knowledge are explicit elements that I have learned through personal experience or was taught by others. They are only useful in certain situations and as such, lay dormant most of the time until a 'relevant' situation arises when they can enter the conscious experience in order to master a situation that is 'problematic'[89]. However, which situation turns problematic in the first place and what is relevant for its mastery depends on what Schutz calls the *systems of relevance*.

While any situation in which I find myself is in principle open to a wide array of experiential possibilities, some specific elements of the situation are usually singled out, enter into consciousness, and are open to further determination and acting upon. To understand this process, Schutz described three systems of relevance: thematic, interpretational, and motivational[90], which form the driving force of the subjective stock of knowledge and "govern its dynamics and use" (Campo 2015 p.142). For each of these, he further distinguishes between *imposed* and *intrinsic* relevance.

Thematic relevance is concerned with which objects enter into conscious experience. This can happen in two different ways. On one hand, imposed thematic relevance refers to situations that cannot be met "by applying the traditional and habitual pattern of behaviour or interpretation" (Schutz 1976 p. 231) and something thus "becomes constituted as problematic" (Schutz 2011 p. 107), imposing a change in my thematic field. On the other hand, intrinsic thematic relevance involves those occasions in which I voluntarily change the theme of experience.

Interpretational relevance comes into play when something has entered my thematic field and is in need of interpretation. When this object is "routinely coincident with elements of the stock of knowledge that are sufficiently familiar and certain", interpretation is automatic and no further explication is necessary (Schutz & Luckmann 1973 p. 198). This, Schutz calls imposed interpretational

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89 Schutz' problematic situation in need of mastery (Schutz & Luckmann 1973 p. 116) is somewhat similar to Dewey's 'indeterminate situation' that is in need of determination (Dewey 1998).

90 The distinction between systems of relevance is purely analytic. In everyday experience, they are unified, interdependent, and practically indistinguishable (Schutz & Luckmann 1973 p. 233).

relevance. If, however, further explication is needed for interpretation, Schutz speaks of intrinsic interpretational relevance.

Lastly, *motivational* relevance gives content to every mention of 'problematic', 'interest', 'sufficient', or 'relevant' above, because thematic and interpretative decisions are "motivationally important" for my conduct, my action, my manner of living (Schutz & Luckmann 1973 p. 210). My *interests*, or "the set of motivational relevances which guide the selective activity of my mind" (Schutz 2011 p. 129) put my experience of the current situation "into a meaningful relation with life-plans and daily plans" (Schutz & Luckmann 1973 p.210) in two ways. On the one hand, I act in and understand the world in a specific way *because* I have a certain biographically determined background. My social environment, education, prior decisions and commitments, etc. determine the attitude with which I encounter a situation, which consists of "expectations, hypothetical relevances, plans for acts, skills, and other elements of habitual knowledge, as well as of 'frames of mind' " (Schutz & Luckmann 1973 p. 217). Schutz classifies these because-motives as imposed motivational relevances. On the other hand, intrinsic motivational relevances involve my voluntary orientation towards the situation in terms of in-order-to motives: the conscious goal of my action inspires a series of steps that I need to do *first things first* in order to reach said goal. Some such steps of action can play out completely inside my own mind (e.g., doing simple addition or subtraction). Nevertheless, for most actions to be effective I also need *objectivations* in the outer world. For example, I might need them to communicate with others (e.g., by waving, pointing, speaking, etc.) or to change the outer world to suit my needs.

Some elements of the subjective stock of knowledge are thus objectivated in the outer world in the context of (inter)subjective processes of mastering problematic situations. There are, however, different types of such objectivations. Two of these types are discussed here: products (with a focus on tools) and signs[91].

While most if not all actions that are geared towards the outer world change the life-world and "leave behind traces in lifeworldly objects" (Schutz & Luckmann 1973 p. 272) some of these traces are "motivated changes" to the life-world, or *products* (Schutz & Luckmann 1973 p. 273). Products include tools,

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91 This leaves 'indications' undiscussed since they are less relevant for the reinterpretation of path dependence' basic evolutionary building blocks. For more information see (Schutz & Luckmann 1973 pp. 267-271).

works of art and marks, with tools being especially relevant for a Schutzian understanding of technology. Technological objects[92] can be understood as tools, i.e., they allow for the purposeful alteration of the structure of the life-world[93]. They are experienced “not just as things in the external world (which of course they also are), but rather in a subjective reference schema of interests and contexts of plans” (Schutz & Luckmann, 1973 p. 17). That is, their interpretation mainly relies on understanding their function in the mastery of everyday problems[94], which may include transforming the outer world into objects ready for use[95], lowering the necessary effort to achieve certain goals (e.g., by simplifying the sequence of steps or lowering the investment in or dependence on certain knowledge, like skills), or creating or crossing spatial, temporal, and social boundaries of the situation.

Still, by themselves, tools have a serious limitation: without a way to make clear to others their full meaning or function, it is difficult for them to travel beyond the boundaries of their subjective origin without losing (part of) said meaning or function. To overcome this difficulty, one uses *signs*.

Signs are objectivations that, through processes of abstraction and idealization, have their meaning detached from their situation of origin and can thus be employed to transmit knowledge to others across society. Such signs are organized in larger systems of signs, especially those of (more or less specialized) language or other symbolic systems. With signs, it becomes possible to communicate elements of knowledge (like the inner workings of tools, the recipes for working with them or the goals towards which they are useful) through other objectivations like markings on the tools, manuals, and educational materials.

Having now summarized some of Schutz’ basic insights into the structure of everyday experience, the following sections develop conceptual resources that

92 Schutz does not discuss technological objects as such. Their identification as tools as well as the functions ascribed to them are my own.

93 A motivated change in the form of a product may inadvertently leave traces that were unplanned and might go unnoticed due to them not coinciding with strong interpretational and motivational relevances. In other words, since we are focused on products’ intended functions, unintended side-effects can be difficult to recognize.

94 Post-phenomenology more thoroughly reflects on how technology influences our experience of and action in the world than I can here (e.g., Verbeek 2011).

95 This is reminiscent of Heidegger’s analysis of the essence of modern technology which sets up the world as ‘standing reserve’ (Heidegger 1977).

should be conducive to actor-centred accounts of path dependence. They do so by providing a Schutzian perspective on path dependence's building blocks (i.e., adoption, technology and the social selection environment) starting with 'adoption'.

4.4. A Schutzian Perspective on Adoption

From an agent-centred standpoint, technology adoption always presupposes that an agent makes choices and undertakes actions. For example, acquisition of a technology implies a choice of the technology as a worthwhile goal, and action being undertaken towards actually acquiring it. As such, a better understanding of choosing and acting as the subjective substratum of adoption seems an appropriate strategy for developing conceptual resources for a thicker notion of agency. To that end, this section delves into Schutz' understanding of the subjective process of choosing and acting (Schutz & Luckmann 1989). Schutz describes this process as consisting of roughly the following more or less conscious episodes (see figure 4.1):

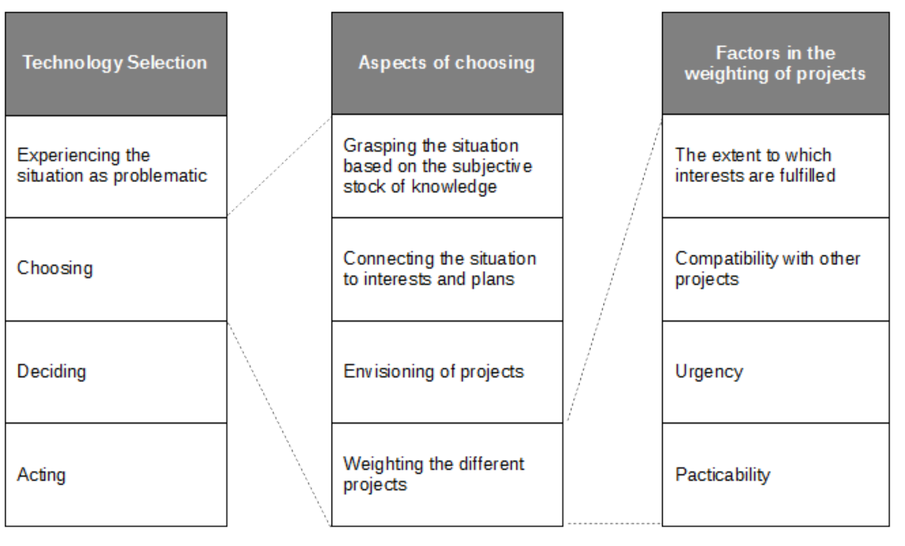

Figure 4.1 Structure of the process of choosing and acting, based on (Schutz & Luckmann, 1989)

The process is first initiated by the experience of a situation as *problematic*. Based on thematic relevances, certain objects enter into experience as problematic. When the open elements of the situation cannot be habitually settled (e.g., it is not automatically clear what the object is or what needs to be done), the would-be actor will have to choose.

The second episode indeed consists of *choosing*. Given the 'openness' of the problematic elements of the situation, one must choose the specific project that one is to act out from an in principle infinite amount of possibilities. According to Schutz, choosing includes several important aspects.

One aspect consists of *grasping the situation* based on the subjective stock of knowledge. The experience of the problematic situation is determined by one's subjective stock of knowledge and imposed and intrinsic interpretational relevances. This not only includes the fundamental elements of the stock of knowledge (e.g., the basic categories of common language), but also the habitual and specific elements of knowledge that are relevant and can be brought to bear on the situation. The adequacy of these elements of knowledge for grasping the situation determine which parts of the situation get taken for granted (imposed interpretational relevance) and which are 'open' for explication and manipulation (intrinsic interpretational relevances).

Additionally, the problematic situation (as grasped based on the subjective stock of knowledge) is connected to the would-be actor's *interests and plans,* since its active mastery depends on how its further explication or manipulation could contribute to these interests and plans[96]. The would-be actor usually has a diverse range of such interests and plans (often connected to social roles and responsibilities, e.g., engineer, citizen, parent, etc.). As such, different and even conflicting interests may be taken as the starting point for the next aspect of the process of choosing: envisioning ways of acting upon these interests.

Any purposive action is indeed preceded by the *envisioning of projects,* which "consists in an anticipation of future conduct by way of phantasying" (Schutz 1973 p. 68). In such phantasying, one first has to envision the state of affairs that one would want to bring about with future action. It is then possible to reconstruct the sequence of single steps that would bring one there, or what I call an

96 These interests and plans act as imposed motivational relevances, some of which are part of the attitude with which the situation is encountered.

in-order-to sequence[97]. When multiple projects have been envisioned as possibilities for mastering the problematic situation, they need to be weighed before a choice between them can be made.

Weighting the different projects against one another is the last aspect of choosing, the outcome of which is determined by a number of factors[98]. First is the extent to which *interests* are expected to be fulfilled. As mentioned, envisioned projects are fuelled by the interests appealed to by the problematic situation. The better a project is expected to fulfil these interests (if successful), the more appealing it is for guiding future conduct. Secondly, Schutz' claim that "[i]nterests have from the outset the character of being interrelated into a system. [...] also actions, motives, ends and means, and, therefore, projects and purposes are only elements [...] projected within a system of higher order" (Schutz 1973 p. 93), indicates that *compatibility* with other interests and overarching plan-hierarchies is also an important characteristic of appealing projects. The third factor is that of *urgency*. On the one hand, a project may be a necessary step towards the fulfilment of other interests and plans, thus gaining urgency under the 'first things first' idealization. On the other, the problematic situation may urgently require action, for example, because it poses an immediate threat or because it is one's responsibility to act. Finally, one has to consider the factor of *practicability*, which involves 1) an "estimation on the part of the would-be actor that the objective conditions for reaching his goal [...] are given", and 2) "the conviction that his own 'capacities' are sufficient to make the performance of the steps of the act practicable" (Schutz & Luckmann 1989 p. 25). Practicability thus also involves an estimation on the part of the would-be actor of the plausibility of plans.

After all this, one project is usually chosen as the most appropriate for mastering the problematic situation.

The third episode that Schutz discusses is that of deciding. Since the process of choosing happens in the inner *durée* of consciousness, and precedes any motivated action in the outer world, the project that ends up being chosen is not yet

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97 This can then act as intrinsic motivational relevance.

98 Simply listing these does not do justice to Schutz' more nuanced description of weighting projects. However, it allows for his insights to be clearly connected to explanations for path reinforcement in section 4.7.

translated into action. The would-be actor first needs to *decide* for that to happen. Such a decision, which is an act of will, links the chosen project to action.

Finally, *the fourth episode consists of acting out the chosen project* by going through the related in-order-to sequence. For those projects that require "action that in its design necessarily engages in the surrounding world" (Schutz & Luckmann 1989 p. 10) and where these changes to the world are "not a purely accidental effect of action [but] must rather be intended and inserted in the plan of action" (Schutz & Luckmann 1989 p. 12), action is called *work*.

In doing work, the actor acts upon the capacities that she presumes to have and which were important in determining the practicability of the project. In other words, work involves the capacities necessary to achieve projected outcomes. Finding resonance with Giddens' rather straight-forward suggestion that "the capacity to achieve outcomes" defines power (Giddens 1984 p. 257), it might be useful to consider Giddens' other suggestion that power is determined[99] by two types of resources: allocative and authoritative. Allocative resources refer to "capabilities [...] generating command over objects, goods or material phenomena". Authoritative resources, on the other hand, refer to "types of transformative capacity generating command over persons or actors" (Giddens 1984 p. 33). Along similar lines, an actor doing work might be said to have two types of capacities. First, she has the capacity to create new or mobilize existing objectivations so as to change the structure of the outer world in accordance with her goals. These objectivations include material features of the environment, means of material (re)production and other produced goods (Giddens 1984 p. 258). However, since the life-world is essentially shared with others, most of these objectivations intentionally or unintentionally impact others' experiences and actions, which leads us to the second type of capacity. That is, the actor has the capacity to get others to act in accordance with her goals, which involves the creation of *imposed relevances* for others, be it thematic, interpretational or motivational (Dreher & López 2015; Dreher 2013; Goettlich 2011). As mentioned above, this might include the creation or mobilization of certain objectivations (e.g., walls, fences and alarm systems aim to keep people out of a power plant). More importantly, however, specific ways of understanding and valuating the

99 Put more accurately, power is generated "in and through structures of domination. The resources which constitute structures of domination are of two sorts – allocative and authoritative" (Giddens 1984 p. 258).

life-world (in the form of symbolic systems) are put forward that are able to shape every part of others' process of choosing as described above.

With this, Schutz' phenomenological analysis of the process of choosing and acting has been adequately summarized. The following section shows how it is compatible with the abovementioned characteristics of structurational agency and with different ways of adopting technology.

4.4.1. Linking Schutz' description of choosing and acting with technology adoption and structurational agency

In the previous section, the subjective process of choosing and acting has been laid bare. This description provides a number of conceptual categories and resources that a) are iterational, projective and practical-evaluative, and b) link up to different ways of understanding technology adoption (and thus to possible self-reinforcing mechanisms in path dependence).

Starting with the latter, different ways in which technology can be adopted are reflected in the specific ways in which technological objects can play an important role in the process of choosing and acting[100].

First, technological objects can be part of the actor's allocative or authoritative capacities in acting out a project. That is, they can function as tools towards the goal of the project. This corresponds to a notion of adoption as choosing to *use* the technological object. This can lead to learning effects as the technological object is used in mastering problematic situations.

The second notion manifests itself when the technological object is the goal of the current project (i.e., it is part of my interests and plans towards which a project was envisioned). This corresponds to another but related notion of adoption: *acquisition*, which, even without learning effects, could contribute to path self-reinforcement through economies of scale. The fact that use and acquisition are recognizable is hardly surprising, since they are probably the most straightforward ways in which technology can be adopted (e.g., Hall & Kahn, 2003)

100 Some other models for technology adoption are based on similar subjective processes, albeit less phenomenologically grounded. See, for example, the five stages of the adoption process in the 'diffusion of innovations' approach (Rogers, 1995).

The third way of adopting technology refers to the possibility of the technological object being adopted only as a *future prospect* whereby, in accordance with the 'first-things-first' idealization, an actor must wait or complete other projects before acquisition and/or use become possible. This means that for the current project, according to the two types of capacities, certain objectivations need to be created or mobilized or other people need to (be made to) adapt their behaviour towards this future technological prospect. This is especially important where the planning, regulation, production, acquisition, or operation of a technological object transcends the capacities of any single person or even most organisations[101].

The last way in which technological objects feature in choosing and acting is not usually seen as a form of adoption, despite the fact that it involves technological objects playing an important role in choosing and acting. It refers to when technological objects (or the consequences of using them) enter into experience *as problematic*, prompting choices and actions to rectify the problem. For the purposes of this paper, I call this 'negative' adoption as opposed to the more 'positive' notions of adoption above[102]. This is important for path reinforcement because negative adoption of non-dominant technologies can reinforce a dominant path (which could be reinforced by negative externalities to adoption of the dominant technology). Moreover, actors can go to great lengths to avoid others experiencing the dominant technology as problematic. In so doing, they avoid weakening the technological path[103]. Notwithstanding, including the possibility of negative adoption also opens up possibilities for endogenous change in path dependent processes.

In sum, adoption of a technology occurs when the technology is recognized and occupies an important place in an agent's subjective processes of choosing and acting. It includes acquisition (as the goal of a project) and use (as tools), but

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101 This is more elaborately discussed in section 4.5.

102 Negative adoption does not coincide with the notion of 'negative externalities'. The latter do not necessarily involve a technology being experienced as problematic. Rather, negative externalities to positive adoption of a specific technology simply lower the chance of positive adoption of other technologies.

103 For example, during the early decades of nuclear energy in the USA, far-reaching secrecy withheld information that may otherwise have caused many more people to experience nuclear energy as problematic (Bergen 2016a).

also incorporates the technology featuring as a future prospect and it being experienced as problematic.

As said, the process of choosing and acting as described above is also compatible with a structurational notion of agency, since it describes a process that is iterational, projective and practical-evaluative.

We can see the iterational aspects of choosing and acting first and foremost in the possibility of habitual settlement of problematic situations, indicating that some solutions to well-known problems are thoroughly routinized. However, even if the agent has to choose, she still does so based on her subjective stock of knowledge. This includes iterational aspects because of the importance of habitual knowledge for grasping the situation, but also the role of skills, useful knowledge and knowledge of recipes in envisioning projects for fulfilling the interests at stake. Lastly, routinized ways of dealing with a problematic situation also add to the practicability of a situation.

The projective aspects of choosing and acting are most clearly connected to the envisioning of projects, in which a desirable future state of affairs and a sequence of steps towards it are envisioned. However, the initial connection of a problematic situation with interests and plans as well as the different aspects of weighting the different envisioned projects (the interests at stake, compatibility with other interests, urgency and practicability) indicate a "future-orientedness in terms of scenario's for action with regards to one's interests, desires, etc." (Araujo & Harrison, 2002 p. 8).

Lastly, it would be difficult for a process of choosing and acting not to be practical-evaluative. However, Schutz' phenomenological description of choosing indicates that it is a complex process that is heavily reliant on one's interests and plans, and the centrality of problematic situations, whereas the envisioning of projects and their evaluation shows a focus on practical judgement.

Thus, next to being compatible with different ways of adopting technology, Schutz' phenomenology of choosing and acting is in line with a structurational notion of agency since it contains the conceptual resources for describing agents' processes of choosing and acting in a way that is iterational, projective and practical-evaluative. However, as indicated in section 4.2, these conceptual resources for a structurational notion of agency also need to be interconnected with the structures in which this agency is exercised and be compatible with the different explanations for path self-reinforcement. To this end, sections 4.5 and

4.6 provide a Schutzian perspective on the two other evolutionary building blocks of path dependence, i.e., *technology* and the *social selection environment* respectively. These descriptions find their basis in a phenomenology of everyday life and as such, are meant to describe the interrelatedness of subjective agency with the structures discussed rather than provide exhaustive new descriptions of already well-studied socio-technical phenomena.

4.5. A Schutzian Perspective on Technology

In section 4.3, it was established that technological objects basically function as tools. However, this straight-forward characterization does not fully appreciate Schutz' insistence on technology's impact on the life-world[104]. More importantly, it is also insufficient to show the interrelatedness of these objects with agents and the social structures in which they find themselves. The following sections present additional considerations concerning the interrelatedness between technological objects and society that are inspired by and structured around some of Schutz' relevant insights.

4.5.1. Making technologies work: recipes, roles, and dependence on others

My ability to do work involving tools, i.e., to act purposefully using technology depends on whether I possess the necessary knowledge to do so. Not only do I need to recognize an object as a tool of a certain type, but I need sufficient knowledge in terms of skills and recipes for action of how to handle it, at least to the extent that allows me to experiment or 'muddle through' the situation. As Schutz indicates: as long as I can do work with technological objects, even "the most complicated gadgets prepared by a very advanced technology", I do not need to know "the Why and the How of their working" (Schutz 1946 p. 463). If, however, the technological object does not function properly and/or my knowl-

104 As Schutz indicates, "[t]he power of making tools expands the range and multiplies the instruments of the psyche, but the tool-maker or commodity-maker obtains power over society when society has begun to think these wares indispensable." (Schutz 1952 p. 233). In a globalized and technologized world, "our social surrounding is within the reach of everyone, everywhere; an anonymous other, whose goals are unknown to us because of his anonymity, may bring us together with our system of interests and relevances within his control" (Schutz 1946 p. 473).

edge of it turns out to be insufficient, I am often dependent on others that I know to have capacities that I do not. These capacities might include tools for repairing it, more intricate knowledge about its inner workings, or simply knowing the right manual or people to refer me to. That is, when technological objects become problematic, I often depend on others whose capacities transcend my own.

This dependence on others when it comes to the creation and troubleshooting of technological objects (especially very complex ones) indicates a division of labour that, while experienced differently by all involved, is also to some extent known or knowable to them. For example, when I buy a car, I realize that there are 'car mechanics' that I could visit in case it breaks down, and that the car was created by 'engineers' and 'workers' as part of 'car companies' (just as they might know me as a 'user' or 'customer'). As such, they are not subjectively understood in terms of specific "personal types", but rather in terms of relatively anonymous "functionary types", (Schutz & Luckmann 1973 p. 82), often as part of collectives like companies or administrative bodies that I also know to have clear functions or goals. Such relatively anonymous functionary types allow for the inclusion of others in larger plans and plan-hierarchies, since understanding them in terms of expected conduct (analogous to functions for tools) makes them more predictable and thus makes plans more plausible and practicable.

4.5.2. Technological Hierarchies – Social Hierarchies – Plan Hierarchies

The making of technological objects also involves the creation of three kinds of interconnected hierarchies[105].

Most obviously, technological objects are usually created out of other technological objects (parts), and will be combined with other tools when used by actors

105 Callon (1991) points out that the more structured and interrelated techno-economic networks are, the more inflexible they become. Something similar might be true of the different hierarchies presented in this section. Also, the power of planning in which time, space, tools and functionary types (and as such, others) are connected and arranged (as they are in the three types of interconnected hierarchies) bears resemblance to the power ascribed to so-called 'centres of calculation' (Latour 1990).

doing work[106]. They are part of *technological hierarchies*. In order to create these parts and bring them together I need to have an idea what parts are available to me and which ones I still need to create or have created, whether their acquisition is feasible, how to put them together, etc.

For most technologies, this also means that I depend on others because they make the parts I need (other manufacturers), they have the expertise for figuring out which ones I need or how to put them together (engineers), they have the know-how to imagine new parts (R&D), are able to get my products to users (distributors), they have the financial resources I need (investors and consumers), etc. As such, the creation of technological objects relies on getting others to act in such a way as to support my plans for the creation of these technological objects, i.e., it involves the creation of *social hierarchies*.

For some technologies, like complex infrastructural systems, actually doing work with the technology requires further meticulous planning and enrolling others (whether individually or in group) into precisely defined roles with specific responsibilities (which act as imposed thematic and motivational relevances). Successful coordination of both tools and others requires the creation of objectivated and systematic *plan hierarchies*[107], including a more or less detailed overview of projects with their proper in-order-to sequences for myself and others to act out. This is possible because I know 'of' others in terms of functionary types. For example, I may know that I need a software engineer, but I do not need to have a specific one in mind for drafting my plans[108].

For many actors, getting them to act 'according to plan' can be reasonably guaranteed by the exchange of highly generalized resources like money for more

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106 What is experienced as the technological *object* is determined by its fit into the pragmatic mastery of the situation. For example, many people might treat a nuclear power plant as one object most of the time: an interpretation that is sufficient to their ends (although that sufficiency may deteriorate in case the experience of the power plants turns problematic, e.g., in case of a nuclear disaster). Engineers operating the power plant, on the other hand, would consider the plant's 'parts' as technological objects in their own right since they feature prominently in their work.

107 Seeing technological objects as composites connected to forms of organisation and objectivated plan hierarchies might well be compatible with a 'richer' conception of path dependence (Martin 2010 p. 19-20).

108 This is reminiscent of David's discussion of role typing and institutionalization (David, 1994), also based on functionary types (Berger & Luckmann, 1966).

specialized ones like research, specialized labour or specific tools[109] (although others may require a different approach, e.g., through contracts providing future certainties, propaganda, rules and regulations set by 'proper' authorities, etc.). Of course, the chance of actually getting others to act according to plan increases the more that doing so is *experienced* by them as relevant. For example, customers are more likely to buy the technological object I create when they *think* that these tools I make are particularly suited for solving their problems or fulfilling their interests, i.e., "when society has begun to think these wares indispensable" (Schutz 1952 p. 233). This highlights the potential of providing others with specific ways of experiencing the world so as to influence their choices and actions (e.g., through advertising). Note that this implies exceptional power for a tool maker that is simultaneously a recognized authority for knowledge-making about the problem the tool is supposed to address[110].

With the Schutzian perspective on technology laid out, we can now turn to the 'social selection environment'.

4.6. A Schutzian Perspective on the Social Selection Environment

As shown in Section 4.4, actions (e.g., those involving technology adoption) presuppose a subjective stock of knowledge, including interests and plans, habits and recipes for action. However, action does not occur in a vacuum: it occurs in society and involves others[111], with whom I can quite effectively and efficiently interact, compete, coordinate, and cooperate. This is only possible because we have a lot of knowledge in common. This is so because much of the subjective stock of knowledge is not all being derived from subjective explications of problematic situations. Rather, much of it was taught to me by others from a

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109 The relative specificity of these resources for a limited number of plans might explain why such investments are seen as sunk costs or 'micro-level irreversibilities' (David 2007). Since the resulting resources are only useful towards my plan, they may not be useful to many others or to plans I might want to act out in the future. Hence, I am 'stuck' with the results of my transaction.

110 This has sometimes been the case with the agencies responsible for nuclear energy production (Bergen 2016a).

111 That is, "[h]umans are the ones who can do or not do something. And humans are humans – and first become humans at all – only among their kind. In other words: the person who acts is in society" (Schutz & Luckmann, 1989 p.66).

wider *social* stock of knowledge. For the Schutzian process of choice, four elements derived from this social stock of knowledge are especially relevant:

- the unquestioned every-day social life-world within which any inquiry starts,
- the socially approved elements of knowledge that can be taken for granted (including a number of interests and plans that are considered 'normal' to have),
- the procedures that are considered appropriate for mastering the situation, whether they be "practical, magical, political, religious, poetical, scientific, etc.", and
- the typical conditions under which a problem can be considered as solved. (Schutz 1973 p. 351)

These elements influence every step of choosing. The grasping of the problematic situation occurs in terms of the unquestioned matrix for inquiry and the elements of the subjective stock of knowledge. It is then connected to plans and plan hierarchies, some derived from one's socially recognised identity or role. Envisioning projects is helped if the necessary knowledge (including recipes for action and knowledge of *tools*) for mastering the problematic situation are available in the social stock of knowledge, and the procedures for weighting these projects can be similarly socially derived. For example, an engineer might come up with different ways of dealing with a risky situation than others, and she may resort to procedures for weighting these projects that seem authoritative to her. For example, she might apply quantitative risk assessment, cost-benefit analysis, next to more generally authoritative procedures like price comparisons, or following legal prescriptions.

However, as this example indicates, there is not one homogenous social stock of knowledge. Rather, it is divided into generally relevant knowledge on the one hand, and relatively specialized knowledge that corresponds to specific roles on the other[112]. Since no single person can specialize in everything nor can she single-handedly carry out everything, an important part of the social stock of

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112 For example, the specific operations of the engineer are not equivalent to the experience of everyday life in that they involve highly formalized systems of calculability and justification. Nevertheless, the general stock of knowledge provides the substratum on which this formalized action is built, and the pragmatic motive still undergirds the world of the engineer.

knowledge is knowledge *of* the structure of specializations and the tasks and authority[113] that go with these. Knowing such a "typology of experts" (Berger & Luckmann 1966 p. 95) allows one to navigate a complex social world, plan projects, enrol others in them and coordinate their actions, e.g., as described in section 4.5[114].

Finally, it is important to note that even if the social stock of knowledge is an impressive collection of imposed relevances, choosing and action are still properly subjective processes because in everyday life, "the social stock of knowledge is divested of its social character [...] It appears in the form a taken-for-granted subjective possession" (Schutz & Luckmann 1973 p. 319). Because of this, the capacity to determine the contents of the social stock of knowledge is a way to impose relevances on others (and thus influence their choices) without necessarily eliciting the impression of oppression[115].

Sections 4.4, 4.5 and 4.6 provided a Schutzian perspective on the basic building blocks of path dependence: 'adoption', 'technology' and the 'social selection environment'. Section 4.4.1 already presented how the Schutzian perspective on adoption, i.e., as founded in the phenomenology of choosing and acting, is compatible with different ways in which technology can be adopted by agents (i.e., through use, acquisition, as a future prospect, or as problematic) as well as with agency that is iterational, projective and practical-evaluative. Now that the Schutzian perspective on technology and the social selection environment have also been presented, it is possible to show how the Schutzian process of choosing and acting relates to the different explanations for path reinforcement.

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113 This authority is important in determining the credibility of claims made by the supposedly authoritative party. As such, authority is important in changing or maintaining the social stock of knowledge which both implies and (re)produces structures of power.

114 The compatibility of the relevant elements of the social stock of knowledge shared by persons responsible for sub-tasks of a project is another prerequisite for effective coordination. While some such elements are only useful in select communities (e.g., radiotoxicity decay rates), others are extremely widespread (e.g., general Standards for Weights and Measures (Latour 1999)).

115 For nuclear energy technologies, such influence has often been exercised through so-called socio-technical imaginaries, i.e., "collectively imagined forms of social life and social order reflected in the design and fulfillment of nation-specific scientific and/or technological projects" (Jasanoff & Kim 2009 p. 120).

4.7. Linking Schutz' Description of Choosing and Acting with Explanations for Path Reinforcement

This section aims to show how the concepts from the Schutzian analysis of choosing and acting fit with the utilitarian, functional, legitimacy, and power explanations for technological path reinforcement briefly introduced in section 4.2. Of course, since technology adoption is what drives the mechanisms on which these explanations rely, the process of choosing and acting underlies all of them. However, as the rest of this section shows, the different explanations emphasize different aspects of choosing and acting for their explanatory work. In exploring these connections, the insights from the Schutzian perspective on technology and the social selection environment are employed to mediate this relation when necessary.

4.7.1. Utilitarian Explanations

In *utilitarian explanations* for path reinforcement, agents adopt a technology if it provides most benefits in comparison to the costs involved, and is better in that regard than competing technologies. A path could thus get reinforced if the efficiency of the leading technology increases (or is perceived to increase) more than that of competitors as more agents adopt the technology (Mahoney 2000)[116]. The mechanisms involved include positive ones that directly reinforce the dominant technology, such as those based on increasing returns (e.g., economies of scale, learning effects, network externalities, etc.). However, mechanisms that indirectly support the path by making competing technologies less attractive (e.g., negative externalities) can also drive utilitarian explanations for path reinforcement.

This focus on efficiency increase finds it phenomenological correlates in two specific aspects of the process of choosing that are involved in the weighting of projects. On the one hand, learning effects from using a technology may allow for its improvement, in turn increasing the *extent to which interests are fulfilled* by using said technology. On the other hand, utilitarian explanations for path reinforcement are at work when adoption of a technology increases the *practicability* of future projects in which the same technology finds 'positive' adoption

[116] This is still highly dependent on the specific returns regimes of the different technologies available (see, e.g., Arthur, 1989; Page, 2006)

(i.e., as a tool, as the goal of the project, or as a future prospect) or decreases the practicability of projects in which other technological objects with the same function (i.e., competing technologies) would find positive adoption. Given that practicability of a project involves a) an estimation by the would-be actor that the conditions for reaching her goal are given and b) that she believes her capacities to be sufficient (Schutz & Luckmann 1989 p. 25), it can also be explicitly coupled with a number of well-known mechanisms for path self-reinforcement such as increasing returns, some examples of which are presented below.

First, increased adoption can convince possible future adopters that the objective conditions for the success of the current project and future plans are given. That is, as acquisition and use of a technology continues, uncertainty about its reliability, quality, etc., decreases, which in turn increases the *plausibility* of projects in which the technology finds positive adoption, especially those involving the technology for acquisition and as a future prospect. This corresponds to mechanisms based on adaptive expectations (Arthur, 1994).

Secondly, people adopting the technology can *lower the necessary capacities* for the execution of the project. For example, in cases where the technological object is the goal of the project, acquisition may be facilitated when increased adoption lowers prices due to scale economies[117]. Where the technological object is a tool in the execution of the project, the results of learning by previous users decreases my need for investment in the necessary knowledge and skills, facilitating the decision towards acquisition and subsequent use.

Finally, increased adoption may increase practicability by *increasing an agent's capacities*. For example, learning effects due to adoption as 'use' can increase practicability by giving tool producers the capacities for tool improvement or by having users develop better skills, routines or recipes for action. Such investments in habitual elements of knowledge can also be understood as a sunk cost because they tend to be technology-specific, in which case other technologies become less attractive in comparison because of the investment in new skills involved[118].

117 Note that this mechanism describes a process in which consumers' buying behaviour increases the producer's authoritative capacities, including the possibility of lowering prices.

118 This phenomenon is also known as 'technical interrelatedness' (David, 1985)

4.7.2. Functional Explanations

As shown above, the choice between technological alternatives is partly determined by the practicability of projects in which technologies find positive adoption. This includes the consideration of how well the technologies, as tools, fulfil the function according to which they are recognized and understood. For *functional explanations* of path reinforcement, however, adoption of a technology is driven by its 'functionality' in or for a *larger system*. As such, the specific efficiency of a technology is less important here than are the consequences of the adoption of that technology for the system of which it is part (e.g., adaptation or survival of the system)(Mahoney, 2000). Self-reinforcement in functional explanations can occur when the positive effects of the technology on the system become clear, which causes additional adoption of the technology, which enhances the technology's capacity to fulfil the function, etc.

This of course means that there can be reasons for agents to prefer one technology over another based on the larger 'systems' of which the technology is a part. In terms of the Schutzian perspective on technology: functional explanations revolve around the consequences of the adoption of a technology for the distinctive technological, plan, and social hierarchies associated with the technology, since these hierarchies inform which other interests are pursued, other projects are envisioned and carried out, other technologies may be adopted, etc. As such, even if technologies are functionally[119] equivalent, they can be compatible with other interests, plans and projects because of the differences between the hierarchies involved in making them work.

As such, functional explanations of path reinforcement refer to cases in which the choice between technological alternatives is determined by a different aspect of the weighting of projects during choosing: the *compatibility* between the technology (including the hierarchies that make it work) and other interests and projects, even if those have little to do with the technology's function as a tool[120]. Given that this compatibility is partly determined by the hierarchies featuring as resources in envisioning and acting out other projects, functional

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119 'Functionally equivalent' is used in the sense that they perform the same function as tools and are similarly practicable in projects in which the technology is positively adopted.

120 That is, a technology's explicit function as a tool may or may not have much to do with the 'function' it serves in larger systems. For example, one 'function' of nuclear energy technology in India was to increase indigenous industrial and engineering capacities (Ramana 2007; Tomar 1980), which scarcely depends on how well the reactors produced energy.

explanations can also be said to depend on the increased fulfilment of interests by and practicability of *other* projects rather than those in which the technology finds positive adoption.

4.7.3. Legitimacy Explanations

According to legitimacy explanations, agents adopt a technology when they perceive it to be right or proper. Self-reinforcement occurs when the initial adoptions set a precedent for what is considered appropriate or legitimate. Additional adoptions occur because they are the appropriate thing to do, which further reinforces the legitimacy of the technology.

According to the Schutzian perspective on adoption, for someone to perceive a technology as 'right or proper', it is necessary for her to have knowledge of, and commitment to, *interests, plans, etc. that are to be prioritized over others*. As indicated in the Schutzian perspective on the social selection environment, these interests and plans are often derived and subjectivated from the social stock of knowledge through upbringing, education, etc. They act as imposed motivational relevances and are part of the attitude with which a technology is experienced.

In this regard, two parts of this social stock of knowledge are especially relevant. First, there are the socially approved elements of knowledge that can generally be taken for granted and form the background of many situations[121]. This includes the elements of knowledge in terms of which the situation (including technology) is to be interpreted, but also general interests such as increasing safety or security, or general plans such as restoring lost national prowess[122]. Also included is knowledge of the 'typology of experts' which (in terms of functionary types) allows an agent to know what her own and others' roles are in solving societal problems, e.g., politicians should take political decisions and engineers should design technologies[123]. Secondly, the social stock of knowledge

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121 The less homogenous the population of possible technology adopters is in this regard, the lower the chances of lock-in (Cantner & Vannuccini, 2016), since this increases the chance that other technologies will be positively adopted or that the dominant technology gets negatively adopted.

122 For example, post-World War 2 France saw the general plan to restore the Radiance of France by developing nuclear energy technologies (Hecht 1998).

123 This does not mean that politicians do not influence technological design or that engineers do not engage in politics (Hecht 1998). However, these activities are not explicitly dictated by their functionary types.

includes knowledge of the proper procedures for handling specific problematic situations. In line with knowledge of the typology of experts, this includes procedures of delegation by which an actor is to leave certain decisions to those with the proper expertise or authority. On top of this, it includes some general knowledge about how these experts are supposed to make these decisions.

This differentiation of roles points towards a distinction between 'those involved' in technology adoption based on legitimacy considerations. On the one hand, there are those who *positively* adopt a technology because they a) consider this adoption as right or proper, i.e., as fulfilling those socially derived interests that are prioritized over others and/or b) the adoption is the outcome of what the actor, based on the social stock of knowledge, believes to be the proper procedure for deciding what technology to adopt (including who is involved in that decision, often in terms of functionary types). On the other hand, for those that do not positively adopt the technology themselves, legitimacy can help to avoid its *negative* adoption which could weaken the technological path (e.g., by giving rise to public opposition to the technology). This is possible if the 'properness' of the technology is taken for granted based on the social stock of knowledge[124], or in cases where the technology does become problematic but explication of that situation quickly settles it in favour of the technology's adoption due to the social stock of knowledge containing the elements showing its properness (or lacking the opposite), e.g., research results sufficiently establishing safety, or the fact that all legal and professional prescriptions were followed in deciding on its adoption.

Of course, all this does not explain how this legitimacy comes about, i.e., through active processes of legitimation. However, since such legitimation processes involve the exertion of power through the mobilization of allocative and authoritative resources, they belong to the power explanations for technological path reinforcement.

124 When the technology is not problematic to me and does not feature in the resolution of other problematic situations, one could say that I am 'indifferent' towards it. In such a case, I do not technically *adopt* it. However, such indifference could still affect path dependence and lock-in if my actions provide others with resources. For example, even if I do not care whether my electricity was produced using nuclear or solar energy technologies, my paying for it provides resources to those selling that electricity to me and those resources enable them to increasingly adopt their technology of choice.

4.7.4. Power Explanations

Power explanations maintain that technological path reinforcement occurs due to the support the technology receives from an elite group of actors. Self-reinforcement can occur when the adoption of the elite-supported technology acts to further increase the power that the elite group has to ensure (or increase the chance of) future adoptions[125].

Such actors' status as elite is defined by the disproportionate power they have to provide such support successfully in comparison to others. As explained in the Schutzian perspective on adoption, the power an actor holds refers to the allocative and authoritative capacities she has to achieve her goals. In other words, power refers to those capacities that allow for 1) changing the structure of the outer world in accordance to her goals, and more importantly 2) to get others to act in accordance with her goals through creating imposed relevances for others (Dreher & López 2015; Dreher 2013; Goettlich 2011) which could influence their processes of choosing and acting. If such influence on others by an elite group of actors is to lead to power-based path reinforcement, however, it will have to be applied on a sufficiently large scale. Based on the above, this can happen in at least two ways.

First, creating (and enrolling others into) the social and plan hierarchies necessary for making a technology work is a clear example of exercising power to get others to work towards the technology's success. However, this does not mean that these others actually positively adopt the technology, since they only execute small projects in the corresponding plan hierarchy. However, to the extent that they depend on the technology's presence and functioning (e.g., because they get paid for working on it), being part of the technology's social hierarchy helps to avoid them negatively adopting it. When the social hierarchy is very encompassing (e.g., because it involves all citizens in a technological project of national importance), this can have particularly profound effects.

Secondly, an elite group might have the power to determine the contents of the social stock of knowledge (or its relatively specialized subdivisions), including its systems of relevance. Such deliberate determination of the social stock of

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125 As such, power explanations might be particularly useful in analysing situations where competition is not very fair nor effective, interests are concentrated, the chance of bankruptcy is low or non-existent, etc. (e.g., government). Some have argued that such situations have a higher chance of path dependent processes leading to lock-in (Liebowitz & Margolis, 2013).

knowledge can steer the utilitarian, functional and legitimacy considerations of others. For example, the capacity to determine prices provides an obvious way of increasing the practicability of a technology's positive adoption by others, and the authority to make projections on the technology's future can also increase such practicability by strengthening the plausibility of successful adoption[126]. As such, power clearly has a role to play in utilitarian explanations. For functional considerations, the capacity to connect the technology to commonly supported projects and plans is paramount[127]. For legitimacy considerations, a select group might have the power to set the standards for what is to be considered acceptable (e.g., to define maximum acceptable risk levels) or to define the procedures by which a technology is to be adopted (e.g., through expert opinion instead of democratic means). In all of these cases, power is exercised to either increase the probability of others positively adopting the technology or to avoid them negatively adopting it[128]. As such, power considerations (and the elements of choosing and acting that drive them) are inextricably woven into the other explanations for path reinforcement.

These sections have demonstrated how the explanations for path self-reinforcement emphasize different aspects of the process of technology adoption that underlies them. More generally, they also show that the conceptual resources developed in the Schutzian perspective on technology adoption, technology, and the social selection environment are at least nominally compatible with specific explanations for path reinforcement.

4.8. Conclusion

This paper set out to develop conceptual resources for a 'thick', structurational notion of agency in path dependent processes. Such resources would aid the

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126 For example, part of what fueled nuclear energy expansion in the USA in the 1950s and 1960s were overly optimistic price projections for nuclear energy production issued by the industry and the US AEC, i.e., the experts on the issue (Clarfield & Wiecek 1984; Cowan 1990).

127 For example, the power to determine the connection and compatibility between nuclear power and regaining the Radiance of France in the early decades of the French nuclear energy program was centralized in the governmental *Commissariat à l'Energie Atomique* (Hecht 1998).

128 This includes imposing thematic and interpretational relevances by selectively exposing others to the elements of knowledge in terms of which the technology is to be understood but also by determining what is *not* part of the social stock of knowledge (e.g., through secrecy).

study of path dependent processes from an actor-centred point of view, and could alleviate some of the concerns concerning path dependence' reliance on contingency and its allegedly excessive determinism. Such resources would have to a) incorporate the three characteristics of structurational agency, b) centre around on what drives path self-reinforcement, i.e., they must have something to say on how technology can be adopted, c) highlight the interconnectedness of agency with the structures in which it is exercised, and d) should be at least nominally compatible with different explanations for path reinforcement.

To this end, the basic theoretical building blocks of technological path dependence' quasi-evolutionary underpinnings (adoption, technology, and the social selection environment) were reinterpreted through the lens of Alfred Schutz' social phenomenology, which provided agent-centred theoretical foundations for the resulting perspectives.

The Schutzian perspective on adoption provided a description of the process of choosing and acting that was both compatible with agency that is iterative, projective and practical-evaluative and with different ways of adopting technology, three 'positive' and one 'negative'. Three forms of positive adoption of technology were recognized in choosing and acting: the technology being the goal of a current project (which could lead to its acquisition), its use as a tool in a current project, and holding it as a future prospect to work towards. On the other hand, there is also the possibility of negative adoption, whereby the technology enters into experience as problematic. In principle, the latter creates room for endogenous change in locked-in technological trajectories[129], although the way it would do so concretely would need further study.

The Schutzian perspective on technology and the social selection environment (which are inevitably actor-centred due their phenomenological underpinnings) show that the notion of agency implied in the process of choosing and acting is interconnected with the structures in which it is exercised. They were also useful in the next step, which consisted in showing how the explanations for path reinforcement (utilitarian, functional, legitimacy, and power) rely in different ways on the process of choosing and acting, technology, the hierarchies involved in making technology work, and the social stock of knowledge. Utilitarian explanations rely on increasing the extent to which interests are fulfilled by and the practicability of projects in which the technology

129 Of course, this does not diminish the possibility of lock-in being disrupted by exogenous change.

finds positive adoption. Functional explanations rely on the compatibility of positive adoption of the technology (including its technological, social, and plan hierarchies) with other interests and plans, even if those plans have little to do with the technology's explicit function. For legitimacy explanations, positive adoption depends mainly on the subjectivation of important motivational relevances from the social stock of knowledge, including the typology of experts that describes who has proper authority to decide certain matters and how this is to be done. Lastly, power explanations rely on the exercise of allocative and authoritative capacities by disproportionally powerful actors to explain both increased positive adoption as well as avoiding negative adoption. The most prominent ways of exercising authoritative capacities include enrolling others into a technology's social hierarchy, as well as determining the contents of the social stock of knowledge. In doing so, it is possible to influence utilitarian, functional, or legitimacy-based considerations in others.

As such, The Schutzian perspectives on adoption, technology and the social selection environment provide a number of conceptual resources which could be helpful for describing path-dependent processes in an actor-centred way. That is, they could help to understand why and how agents make the technology adoption decisions that they do, and the way in which technology and the social selection environment mediate those choices and their consequences.

However, some critical notes are also in order. First of all, they should not be seen as a wholesale alternative to other ways of describing or investigating these processes, whether from a historical perspective, modelling, lab experiments, etc. Nevertheless, they might provide inspiration for them, e.g., for modelling agents' decision processes. Also, the perspectives may be more explicitly connectable to other theoretical developments in path dependence studies, even if they are not currently incorporated. For example, combining the perspectives developed in this paper with insights from the exploration of important implications of path dependence' quasi-evolutionary structure by Vergne and Durand (2011) could be quite informative for further connecting actor-centred and structural investigations into technological path dependence.

Lastly, some of the conceptual resources developed in this paper might not be all that specific to technological path dependence. That is, they may also be partially applicable in other theories on technological or institutional persistence, such as escalating commitment, sunk costs, structural inertia, etc. (Sydow et al., 2009). However, this should probably not be a problem for the application of the perspectives to the study of technological path dependence.

5 Reversible Experiments: Putting Geological Disposal to the Test

Conceiving of nuclear energy as a social experiment gives rise to the question of what to do when the experiment is no longer responsible or desirable. To be able to appropriately respond to such a situation, the nuclear energy technology in question should be *reversible*, i.e. it must be possible to stop its further development and implementation in society, and it must be possible to undo its undesirable consequences. This paper explores these two conditions by applying them to geological disposal of high-level radioactive waste (GD). Despite the fact that considerations of reversibility and retrievability have received increased attention in GD, the analysis in this paper concludes that GD cannot be considered reversible. Firstly, it would be difficult to stop its further development and implementation, since its historical development has led to a point where GD is significantly locked-in. Secondly, the strategy it employs for undoing undesirable consequences is less-than-ideal: it relies on containment of severely radiotoxic waste rather than attempting to eliminate this waste or its radioactivity. And while it may currently be technologically impossible to turn high-level waste into benign substances, GD's containment strategy makes it difficult to eliminate this waste's radioactivity when the possibility would arise. In all, GD should be critically reconsidered if the inclusion of reversibility considerations in radioactive waste management has indeed become as important as is sometimes claimed.

5.1. Introduction

Ever since nuclear energy technologies were developed after the Second World War (WW2), we have been learning about the risks of nuclear energy production and how to deal with them[130]. However, more than 50 years after nuclear power

130 The development of Probabilistic Risk Assessment (PRA) is especially noteworthy here, pioneered in the famous WASH-1400 or Rasmussen Report (U.S. Nuclear Regulatory Commission 1975).

plants first supplied electricity to the grid[131], the Fukushima nuclear disaster made it excruciatingly clear that we are nowhere near done learning. Not only are there residual uncertainties about the risks of already widely deployed nuclear energy technologies, but new technologies are being developed (e.g., Generation IV reactors), while older ones have not seen widespread introduction even after decades of effort (e.g., geological disposal of radioactive waste).

However, how is this learning to be organized? The uncertainties and risks connected to nuclear power plant operation and radioactive waste management (RWM) have led van de Poel (2011) to propose that we should consider nuclear energy as a social experiment. This would mean that specific decisions on the acceptability of a technology, which now often occur before its actual introduction into society, would be replaced by an ongoing and conscious process of learning about its risks and benefits, as well as what is to be considered acceptable. So, understanding a nuclear energy technology as a social experiment would allow us to learn more about that technology's risks and benefits as the experiment unfolds. Nonetheless, it also means that we might at one point learn what we, in a sense, would rather not, i.e., that continuing the experiment is no longer responsible or even that it is simply no longer desirable. What is an experimenter to do then? At the very least, she should be able to stop the experiment, and hazards should be contained as far as possible (van de Poel 2011)[132]. In earlier work (Bergen, 2016a) I contended that these two conditions, the ability to stop further development and implementation of a technology (the experiment) and undoing its undesirable consequences (e.g., hazards), are constitutive of technological *reversibility*. In other words, the technology experimented with should be reversible if the experimenter wants to be prepared for the experiment taking a turn for the worst.

This paper further explores what it means for a technology to be reversible by applying the abovementioned conditions for technological reversibility to a technology in which reversibility is already a salient consideration: the geological

131 In 1953, Obninsk, Russia was home to the very first reactor providing power to the national grid. As this was mainly a research reactor, however, its power output was rather limited. By 1956, Calder Hall, United Kingdom housed the first large-scale nuclear power plant, although it also produced plutonium for the British military program. In 1957, the Shippingport Atomic Power Station in Pennsylvania became the first large-scale nuclear power plant that was fully devoted to civil nuclear energy production.

132 These are the two conditions that are most relevant to considerations of reversibility out of a longer list by van de Poel (p. 289).

disposal of radioactive waste (GD). In doing so, the paper also provides an answer to whether or not GD can be considered reversible in the way required for responsible social experimentation.

5.2. Reversibility as an Issue in Radioactive Waste Management

A quick exploration of publications by major nuclear organisations[133] revealed five broad uses of the concepts of reversibility and irreversibility in the field of nuclear energy. The first three uses describe basic processes and consequences that are implicated in the production of nuclear energy:

- (Ir)reversible mechanical/chemical/thermodynamic processes during the production of nuclear energy or radioactive waste management (e.g., spent fuel reprocessing, drilling damage to repository host rock, and nuclear fission)
- A specific but important sub-category of the above: (ir)reversibility of flows and migrations, mostly of radioactive isotopes (e.g., in technical, environmental or geological systems). This aspect is often connected to standards for radioactive waste management facilities.
- (Ir)reversibility of consequences, e.g.:
    - Mutations and cell damage in living tissue due to irradiation
    - Damage to the environment and its ecosystems

While these uses are useful for describing (ir)reversible aspects connected to nuclear energy, they are not actually oriented towards making a nuclear energy technology more reversible. However, the last two uses are oriented as such, since they provide specific design goals or strategies for reversible *radioactive waste management* (RWM) technology and its implementation:

- *Retrievability* of radioactive waste from a waste storage or geological disposal facility.

[133] That is, the websites of the U.S. Nuclear Regulatory Commission (NRC), the International Atomic Energy Agency (IAEA), the OECD Nuclear Energy Agency (NEA), the French National Radioactive Waste Management Agency (ANDRA), the Swedish National Council for Nuclear Waste (KASAM), and the International Commission on Radiological Protection (ICRP) were searched for the terms 'reversibility', 'reversible', 'irreversibility', and 'irreversible'.

- *Reversibility* of (consequences of) decisions during the implementation process of a waste storage or geological disposal facility
(e.g., Interagency Review Group on Nuclear Waste Management 1978; OECD Nuclear Energy Agency 2011; U.S. Department of Energy 1991)

Different RWM technologies differ in their plans for reversibility or retrievability of radioactive wastes, broadly determined by two factors. First, the type of radioactive waste is relevant. Generally, three categories of radioactive waste are distinguished based on their lifetime and radioactivity: low, intermediate, and high-level waste (IAEA 2009)[134]. High-level waste from nuclear energy production can be further divided based on the nuclear fuel cycle from which it results: it usually consists of either unprocessed spent nuclear fuel (SNF) or the still highly radioactive rest products of SNF reprocessing (HLW)[135]. The second relevant factor is the specific stage of RWM. For example, an interim storage facility has different ambitions for retrieving SNF or radioactive wastes than a final disposal site[136].

For many low and intermediate-level waste, disposal and monitored storage (on- or near-surface) are considered realistic solutions until radioactive decay has rendered the wastes sufficiently unhazardous. Interim storage (on-surface, near surface or otherwise) for high-level waste[137] is employed for a) letting it decay and cool down to a point at which they become eligible for emplacement in a dis-

134 This portrayal of the distinction does not include exempt waste, very short-lived waste, and very low-level waste, since they require relatively little or short duration shielding or regulatory control (IAEA 2009).

135 In a fuel cycle without reprocessing of SNF (the 'open' fuel cycle, e.g., in Canada, Sweden, and the USA), SNF is considered high-level waste when it is accepted for disposal. In a fuel cycle with reprocessing of SNF to extract uranium and plutonium for recycling (the 'closed' fuel cycle, e.g., in France, India, and Japan), high-level waste from nuclear energy production consists mainly of the fission products left over from this reprocessing (IAEA 2006), which are normally solidified before disposal. This distinction between HLW from reprocessing and SNF without reprocessing is highly significant: while unprocessed SNF has a waste lifetime of about 200,000 years, reprocessing can reduce high-level waste lifetime to about 5,000 years (Taebi & Kloosterman 2008).

136 Per definition, in the case of *storage*, retrieval of the waste is envisioned for some point in the future, whereas *disposal* implies emplacement of waste without the intent of eventual retrieval.

137 In line with the distinction given above, I use the formulation 'high-level waste' to mean the category as defined by the IAEA (2009), which in the case of nuclear energy production includes both SNF and HLW as presented in footnote 164.

posal facility, and/or b) storing it until disposal facilities are available (Bonin 2010). In both cases, retrievability is an essential design feature. After such storage, however, a more permanent solution is generally deemed necessary for the further management of SNF and HLW, given the immense span of time that these materials remain potentially radiotoxic: geological disposal. A geological disposal facility, or repository, combines the protection offered by stable geological layers deep below the earth's surface with multiple engineered barriers (e.g., overpack, clay, bentonite) around waste packages that contain either solid SNF or liquid HLW from reprocessing that has been stabilized in a confinement matrix (e.g., glass or concrete). All this is supposed to prevent radionuclides from reaching the human living environment until they have reached a safe level of decay (Bonin 2010). Given the time it takes for this level of decay to be reached, emplacement of SNF or HLW in a repository is, for all intents and purposes, meant to be indefinite[138]. This solution supposedly allows the current generation to take responsibility for the radioactive wastes it produces, while not burdening future generations with it, nor counting on the longevity of institutions to maintain waste management practices for thousands of years.

Despite its *ultimate* goal of indefinite disposal of SNF and HLW for the reasons specified above, reversibility is increasingly recognized as a possibly important aspect of GD (e.g., Aparicio 2010; ICRP 2013; OECD Nuclear Energy Agency 2011; Swedish National Council for Nuclear Waste 2010). Arguably, the most systematic proposal that describes how reversibility is supposed to feature in geological disposal has been put forward by the OECD Nuclear Energy Agency (NEA) as a result of their Reversibility & Retrievability project, in which it explored the role of reversibility considerations in GD. According to the NEA (2011):

- *Reversibility* "describes the ability *in principle* to change or reverse decisions taken during the progressive implementation of a disposal system [...] The implementation of a reversible decision-making approach implies the willingness to question previous decisions in the light of new information, possibly leading to reversing or modifying them, and a decision-

[138] Note that this does not mean that actual confinement of radionuclides is guaranteed indefinitely (which is technically impossible), just that the timescales involved prescribe extremely long-term emplacement.

making culture that encourages such a questioning attitude" (p. 23; emphasis in the original).

- *Retrievability*, on the other hand, is "the ability *in principle* to recover waste or entire waste packages once they have been emplaced in a repository. Retrievability is the final element of a fully-applied reversibility strategy" (p. 24; emphasis in the original). Note that this does not mean that all high-level waste will also be practically accessible: past actions such as HLW vitrification might still exclude this possibility.

Both reversibility and retrievability apply here to the period before final closure of the repository, possibly up to 100 years after initial emplacement. Reversibility refers to a step-wise decision-making process, in which previous decisions can be undone. However, reversibility diminishes over time, as actions based on these decisions are partly cumulative and increase the costs and effort involved in undoing past decisions. Retrievability also gets more and more difficult as waste packages get sealed in place and the repository gets backfilled over time (OECD Nuclear Energy Agency 2011). Thus, final closure of the repository also means the end to a realistic possibility of reversibility and retrievability. Indeed, reversibility and retrievability are not considered to be "design goals" for GD. Rather, they are seen by the NEA as "attributes of the decision-making and design processes that can facilitate the journey towards the final destination of safe, socially accepted geological disposal" (OECD Nuclear Energy Agency 2012 p. 22). In other words, they are only instrumental in achieving the ultimate (design) goal of GD that has been set forward since its origins in the 1950's (e.g., National Research Council 1957)[139]: *passive safety*, or safety without human intervention. Still, a number of reasons are put forward as justifying the importance of reversibility and retrievability for GD:

- Reversibility would allow future generations to use the emplaced materials as a resource, especially since SNF contains plutonium and uranium which might have value as a future source of energy.
- Further technical advances might make it possible to render radioactive wastes (more) harmless.

139 For a brief discussion of the evolution of reversibility provisions in GD in the USA, please see section 5.3.4.

- If a repository performs worse than expected, remedial action would be facilitated by reversibility provisions.
- Finally, reversibility can help foster public acceptance of waste disposal facilities, or help adapt waste management if public or policy attitudes change over time.
  (OECD Nuclear Energy Agency 2011)

However, as Barthe (2010) points out: the goal of final disposal of wastes a century after initial emplacement as well as the regressive nature of reversibility and retrievability seem contradictory to these reasons for adopting reversibility in the first place. First of all, it will probably take a significant amount of time to develop technology for using a repository's contents as resources or for making high-level waste less harmful. If this is the case, why would one want to have reversibility and retrievability diminish and possibly disappear before such technology can be developed and implemented on a sufficient scale? Secondly, repository performance becomes significantly more difficult to assure with increasing extrapolation into the long-term future. As such, reversibility and retrievability as a response to worse-than-expected repository performance has a higher change of becoming useful as time goes by. These considerations cast doubt on the extent to which GD could live up to the NEA's own reasons for reversibility given above. On top of all this, it is clear that the choice of technology is a foregone conclusion in the NEA's framework. It is concerned with how to implement a specific technology: GD. Yet, the recognition that changing public and/or policy attitudes towards RWM should be able to influence RWM strategies, as is shown in the fourth reason for reversibility, is of importance here. What if, for whatever reason, GD does not turn out to be the apt solution the technical community takes it to be (OECD Nuclear Energy Agency 1995)[140], and/or democratic considerations would point us towards other technologies? Should our past decision for GD not also be reversible?

If GD reversibility provisions were, analytically speaking, fully in line with the reasons given for these provisions, these discrepancies should not exist. And yet, these discrepancies are here and warrant our attention. In this paper I would like to propose an outlook on technological reversibility that could a)

140 Not only could this happen due to technical difficulties, but also through learning about what we should or should not consider 'apt'.

provide some insights in how technologies like GD become irreversible, b) could help explain why the discrepancies above exist as they do, and c) provide input concerning the way technologies like GD could be made more reversible. In so doing, I explore whether GD can actually be considered a *reversible technology*. If it can, then the above criticisms might be moot. However, it might also turn out that despite the efforts visible in the NEA's Reversibility & Retrievability project, GD cannot be considered properly reversible. If so, we might need to reconsider either GD as the dominant high-level waste management technology or whether, why and to what extent we want reversibility in the first place.

To answer the question whether GD can be considered properly reversible, it is necessary to have an idea of what constitutes a reversible RWM technology. Elsewhere, I have argued that for a nuclear energy technology to be considered reversible, two conditions need to be both met:

- The ability to stop the further development and deployment of said technology in a society
- The ability to undo the undesirable outcomes of the development and deployment of the technology when so desired.
  (Bergen, 2016a)

While arguably adequate as abstract descriptions of what constitutes 'ideal' reversibility, these conditions are not yet sufficiently operationalized to be useful in considering practical cases such as the one presented here. For one, their form does not yet invite either questioning or qualified answers. Secondly, they are not yet case-specific. As such, I would like to rephrase the conditions as two GD-specific questions that, if both answered affirmatively, would show that GD is reversible. These questions are:

1) *Would an authorized body be reasonably able to switch from GD to an alternative solution if problems with GD were to arise?* If not, the first of the conditions for reversible technology would not be met, and GD cannot be considered fully reversible[141].

[141] If it is currently impossible to switch to an alternative, then the technology is not currently reversible. Whether or not some future developments might change this situation has little bearing on the technology's current reversibility status.

2) *Does GD exhaust the possibilities of undoing the consequences connected to high-level waste, and the hazards that could come about due to the use of GD for managing this waste?* Again, a negative answer to this question would disqualify GD as a reversible technology.

In what follows, I deal with these two questions in turn. In section 5.3, the first question is examined by taking a closer look at the historical development of GD through the lens of path dependence and lock-in. I answer the second question in section 5.4, where I propose that the ability to undo undesirable consequences of GD is connected to the choice between different design strategies, and that GD's chosen strategy is less-than-ideal.

5.3. On the Ability to Stop Further Development and Deployment of Geological Disposal

In this section, the following question is considered: would an authorized body be reasonably able to switch from GD to an alternative solution if problems with GD were to arise? To answer this question, it is important to understand why switching to an alternative could become difficult or impossible in the first place. According to the theory of path dependence and lock-in, such difficulties can arise as a result of a historical process of technological development that leads to a situation in which switching to another solution becomes increasingly difficult: the technology becomes locked-in. As such, investigating the development of GD through the lens of path dependence and lock-in could help answer the question at hand. Before discussing GD's historical development and whether it is locked-in or not, the theory behind path dependence and lock-in is briefly introduced below.

5.3.1. Path Dependence and Lock-in

We call the development and implementation process of a specific technology path dependent if that process is determined by its own history (David 2007). That is, due to its specific characteristics, such a process can become inflexible in terms of the practical possibility of changing their course due to them being unable to "shake free from their histories" (David 2001 p. 19). Such path dependent processes, contain two main elements (Arthur 1989):

- A *contingent starting period*. This period is contingent in the sense that it does not originate in a smooth and predictable historical sequence of events but rather that a new element (e.g., the introduction of a new technology) sets history off on a novel path.
- A period exhibiting *'increasing returns'*. Arthur identified four major types of increasing returns: scale economies, learning effects, adaptive expectations and network economies (Arthur 1994). While increasing returns can be conceived of quite narrowly as increasing efficiency, David (2007) considers it more appropriate to conceive of them as "self-reinforcing, positive feedback mechanisms governing decisions such as the choice among alternative production techniques, or consumer goods, or geographical locations for production activities" (David 2007). This self-reinforcement consists of both "positive and negative mechanisms that decrease the likelihood that alternative paths will be selected" (Vergne and Durand 2011). Positive mechanisms directly support the path (e.g. economies of scale or learning effects), while negative mechanisms operate by rendering alternative paths less interesting. As such, these mechanisms sustain the path that was contingently selected.

In some cases, this self-reinforcement can be so efficacious that it leads to an irreversible outcome, i.e., lock-in (Mahoney 2000; Vergne & Durand 2011). While initially options are open and multiple outcomes are possible, path dependence and self-reinforcement lead to (more and more) irreversibility that, without exogenous shock, could be incredibly persistent. If so, the potential for endogenous change becomes rather low (Mahoney 2000).

According to David (2007), one fundamental aspect of these self-reinforcing dynamics or increasing returns is the presence of micro-level irreversibilities, which occur when "a finite and possibly substantial cost must be incurred to undo the effects of the resource allocation decision in question" (David 2007 p. 101). So, these micro-irreversibilities make agents favour certain options for action, while disfavouring others due to the relative opportunities and costs involved in pursuing them. This effect is further strengthened if these micro-irreversibilities are interdependent, since it becomes less favourable to undo specific micro-irreversibilities if this requires undoing others as well. As such, they are constitutive of the self-reinforcement of dominant structures by guiding agents' behaviour towards adherence to the most dominant (technological) solution, eventually strengthening its lock-in and increasing its irreversibility.

Two notes about these micro-irreversibilities are in order. First, different types of lock-in seem to correspond to different sorts of micro-irreversibilities driving path-dependent processes. Indeed, different types of drivers of a technology's lock-in can be found in the literature. For example, there is political (e.g., W. Walker 1999, 2000), institutional (e.g., Foxon & Pearson 2008; W. Walker, 1999, 2000), economical (e.g. Arthur 1989; Liebowitz & Margolis 1995), and infrastructural (e.g., Frantzeskaki & Loorbach 2010; Scrase & Smith 2009) lock-in of a specific technology or technological project or system. While these have a different emphasis on what is most determinative of the lock-in in question, they all refer to sets of *symbolic*, *institutional* and/or *material* micro-irreversibilities that underlie the reinforcing dynamics. For high-level waste management, such micro-irreversibilities cover a spectrum of elements, from stabilization and packaging of HLW, test sites for GD and nuclear reactors producing SNF (material) to preferred methods of risk evaluation, nuclear regulations and policy prescriptions and practices, and institutional commitment (institutional), as well as underlying narratives, themes and values (symbolic). Secondly, it is interesting that non-material micro-irreversibilities could drive path-dependent processes. As such, even if a process of technology development results mainly in institutional or symbolic elements, a technology could (in theory at least) become locked-in without significant deployment of said technology in the real world as long as increasing returns are sufficient to keep actors committed to that technology. Finally, micro-irreversibilities lie at the basis of the positive and negative mechanisms that can lead to lock-in, i.e., make a technology practically irreversible. As such, this framework seems to combine both (ir)reversibilities *within* GD as micro-irreversibilities (which include the matters the NEA's concepts of retrievability and reversibility is meant to address), as well as the (ir)reversibility of GD *itself* as a technology for radioactive waste management.

In what follows I will use the history of civil nuclear energy and high-level waste management in the USA between 1944 and 1987 as an example to show how GD's development can exhibit the characteristics of a path-dependent process. While certainly not an exhaustive example (GD is held to be the appropriate solution in most nuclear energy-producing countries (U.K. Nuclear Decommissioning Authority 2008, 2013)), I hope it is sufficiently powerful for showcasing the type of historical process that lies at the basis of GD's dominance. First, I present a sketch of GD's contingent genesis in the years after the WW2, after which I elaborate on its history from the late 1950's onwards.

5.3.2. Geological Disposal's Contingent Starting Period: Nuclear Development between 1944 and 1957

The contingent starting period that set the stage for our current situation in which GD is the dominant solution for civil high-level waste management in the USA can be situated in the period between 1944 and 1957.

During WW2, nuclear development was dominated by military applications, both in weapons technology (developing the atomic bomb in the Manhattan project) as well as reactor design (producing plutonium for the weapons program). This dominance continued in the years after the war, one result of which was the development of the pressurized water reactor [PWR] for use in submarines[142] (Cowan 1990). Given the circumstances of WW2, this initial focus on developing nuclear applications was rather straight-forward. For all that, these developments were prioritized over the careful and necessary management of the wastes they produced. While in 1944, the first HLW facility was constructed at the Hanford site in the State of Washington to store liquid HLW from the military nuclear program[143], many low- and intermediate level wastes were dealt with through 'dilute and disperse' strategies (Mckinley, Alexander & Blaser 2007; Miller, Fahnoe & Peterson 1954). This early focus on applications rather than proper waste management was further exacerbated by how the Atomic Energy Commission (AEC) was set up in 1946, being responsible for both the promotion as well as regulation of nuclear development. Its focus was much more on promoting the development of nuclear applications than on strict regulation, and secrecy ensured its control over nuclear matters (Clarfield & Wiecek 1984). In combination with relatively small waste volumes and the isolated location of the facilities at which this waste was produced, this led to RWM being basic (if not haphazard) until the early 1950's. In at least one sense, this was surprising: WW2 had graphically shown both the potency as well as the destructive capabilities of splitting the atom. In 1953, however, nuclear safety

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142 Initiated in the late 1940's, the nuclear naval propulsion program launched its first PWR-powered submarine -the USS Nautilus- in 1954.

143 This HLW was apparently stored without concrete plans of its further management, an example of the prioritization of the application end of the fuel cycle. A tremendously complex and expensive clean-up operation is currently ongoing at the Hanford site to properly deal with 40 years' worth of Hanford's HLW in deteriorating storage facilities (Oregon Department of Energy, 2014).

found strong political expression in Eisenhower's 'Atoms for Peace' speech[144], which was to set the stage for the development of a peaceful civil nuclear energy program, separate from the military one. As Jasanoff and Kim (2009) argue, the speech was aimed at symbolically containing the atom's destructive potential so graphically illustrated in Japan only a few years before. It was also aimed at containing international fear of the USA as a nuclear superpower, and was to open the way towards the exploitation of the atom's peaceful applications. With 'Atoms for Peace', then, a strong theme of *containment* of the dangers connected to the atom lay at the basis of the nuclear energy industry. The speech also called for a private nuclear energy industry[145]. This meant limited government influence in the new industry, and making investment in it interesting for private investors. With the 1954 Atomic Energy Act, the patenting of nuclear energy technologies was opened up, and secrecy was partly lifted so that private parties could use previously confidential technical knowledge to develop nuclear energy applications.

After 'Atoms for Peace', the nuclear energy industry indeed started to develop. Since the nuclear energy program was pressured by Eisenhower's intentions into a mode of urgency, a reactor type was chosen with which significant experience had already been accumulated in the military program: the PWR (Cowan 1990). However, a final solution for the disposal of HLW had not yet been settled upon. An important step towards that goal was taken when, at the request of the AEC, the Committee on Waste Disposal of the National Research Council produced a report (National Research Council 1957) that would prove to be foundational for the development of GD and the values or aspirations it embodies. It argued that (after additional research), deep geological disposal could be both a safe and feasible option for HLW disposal, and called for more research into the solidification of HLW which mostly took a liquid form at the time[146]. On top of this, in the case of deep GD, the HLW was to "disposed of

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144 For a transcript of the speech, see http://www.iaea.org/About/history_speech.html (accessed March 29, 2013).

145 What was also contained was the nuclear influence of the USSR. The USA's nuclear industry development had to be privatized in order to be ideologically in line with the American liberal ideal so different from the USSR's statist communism.

146 The report mentions that the Commission was "convinced that radioactive waste can be disposed of safely in a variety of ways and at a large number of sites in the United States" (p.3), adding that the "most promising method of disposal of high level waste [...] seems to be in salt deposits" (p. 4). Moreover, it promotes the "stabilization of the waste in a slag or ceramic

without concern for its recovery" (p. 86). As such, confidence that HLW could be safely contained and disposed of in the near future was established by the Committee's research.

5.3.3. 1957-present: the path to lock-in

This promise of GD as a passively safe future solution for HLW disposal provided the nascent nuclear energy industry with the reasonable assumption of manageable long-term safety, which was important given the risks involved. On top of this, the dominant assumption from the late 1950's until the mid-1970's was that SNF from the civil nuclear energy program would be reprocessed to extract fissionable uranium and plutonium, which would be reused for further energy production[147] (J. S. Walker 2009). As such, the future development of both a civil reprocessing industry as well as GD facilities was considered a sufficient and realistic HLW management strategy. Nuclear authorities stood by the idea that the problem of radioactive waste was technically soluble (U.S. Atomic Energy Commission 1962 p. 55). Also, based on a series of hearings by the Joint Committee on Atomic Energy in 1959, the authorities were convinced that the radioactive waste problem should not slow down the development of the nuclear energy industry and that it would be possible to protect the public during this development (Metlay 1985 p. 236). This confirmed the AEC's confidence in the possibility of safe radioactive waste management and its prioritisation of industrial promotion over HLW management. This attitude endured for over a decade despite a number of incidents at early above-ground HLW storage sites between 1959 and the mid-1970's (Metlay 1985), which nonetheless spurred the adoption of additional safety features in the 1960's and 1970's such as multi-layered storage casks for HLW and the solidification of HLW where it had been

material" (p. 6) as another promising method, away from the predominantly liquid HLW at the time.

147 There was already significant experience with reprocessing technology in the military program. Moreover, the AEC promoted reprocessing out of concern for uranium supply shortages for the nuclear energy industry. Together with the breeder reactors the AEC was looking into, reprocessing would substantially increase the sustainability of uranium resources (Stewart & Stewart 2011).

liquid before[148] (Metlay 1985). As such, additional steps were taken towards the greater capacity to *contain* HLW and its risks.

While the 1960's saw an exponential increase in orders for nuclear power plants, serious practical research into GD was also being undertaken by the AEC, and in 1966 a follow-up committee reaffirmed the conclusions of the 1957 report that GD was the most promising solution for the disposal of HLW (National Research Council 1966). Moreover, the civil reprocessing industry saw its humble beginnings (heavily promoted by the AEC) with the start-up of the reprocessing facility at West Valley, New York in 1966. With a second plant at Morris, Illinois and a third at Barnwell, South Carolina receiving construction permits in 1967 and 1970 respectively, the development of the civil reprocessing industry had apparently been kick-started (Metlay 1985).

In 1970, Lyons, Kansas was proposed as the site for the very first full-scale GD demonstration project[149]. This decision was supported by further research by the National Research Council that confirmed Lyons' adequacy as a pilot facility site and again stressed GD's appropriateness for HLW disposal (National Research Council 1970). However, not everyone shared the AEC's optimism about the safety and appropriateness of the site (there were numerous boreholes present due to earlier explorations for oil and gas and some water migration could not be properly accounted for (Metlay 1985)), and the proposal was dropped two years later for technical and political reasons. Despite this setback, the AEC still pushed for an expansion of the geological disposal program, extending the search for other possible sites for GD. Nonetheless, in the wake of the difficulties with the Lyons site, and as public opposition to nuclear energy was picking up in the early 1970's, other possibilities for HLW management were considered (Vandenbosch & Vandenbosch, 2007). Firstly, an attempt was made by the AEC to implement Retrievable Surface Storage Facilities as a possible medium-term solution for HLW. This proposal was rejected by opponents, including the public, politicians and the Environmental Protection Agency (EPA, set up in 1970), partly out of fear that these facilities would become low-budget permanent solutions (U.S. Congress Office of Technology

148 The 1957 National Research Council report had prompted further research into waste solidification which continued through the 1960's and beyond. In 1970, the AEC proposed new regulations to have liquid HLW solidified five years after its generation (Metlay 1985).

149 An abandoned salt mine near Lyons already served as a test site for HLW disposal between 1965 and 1968.

Assessment, 1985). It was subsequently dropped in 1975. Secondly, several options for the final disposal of HLW were further investigated and compared, like extra-terrestrial disposal, disposing of waste in the seabed, in or under ice sheets in the Arctic, transmutation of certain waste types and indeed, geological disposal (e.g., U.S. Atomic Energy Commission 1974)[150]. On top of these difficulties for the GD program, the reprocessing industry was not at all thriving in the way the AEC had hoped. The West Valley plant stopped operation in 1972, when modifications to solve operational and environmental regulatory issues were deemed uneconomical. The Morris plant, finished in 1974, never came into full operation due to technical problems and equipment failures and was abandoned in the same year. Finally, the Barnwell facility was meant to start operation in 1974, but construction delays and licensing issues prevented that deadline from being met (Stewart & Stewart 2011). In short, the AEC's plans for HLW management were not running smoothly.

Not only HLW management was in some trouble around this time: the nuclear energy industry had to learn the hard way that the optimism about atomic energy "too cheap to meter"[151] was sorely misplaced, especially as the AEC was obliged to enforce stricter regulations on the industry under growing pressure from environmental groups and the EPA. As such, orders for power plants dropped significantly. This same pressure laid bare the conflict of interest the AEC operated upon (promoting as well as regulating the nuclear energy industry), which led to the AEC being disbanded by the Energy Reorganization Act in 1974, its responsibilities split between the Energy Research and Development Administration (ERDA; promotion) and the Nuclear Regulatory Commission (NRC; regulation, licensing, materials management and setting of safety standards)(Stewart & Stewart 2011). This led to even stricter regulation, which increased costs and made it even more difficult to get licenses for nuclear power plants (Clarfield & Wiecek 1984). As the expansion of nuclear energy production capacity was slowly grinding to a halt in the latter half of the 1970s, the societal pressure that previously led to the disbanding of the AEC rekindled

150 Although some of these options had at times been considered, this was the first time they were as officially and systematically compared.

151 This phrase was coined by the chairman of the AEC, Lewis Strauss, in a 1954 speech to the National Association of Science Writers (Strauss 1954). While it has become iconic of the economic optimism at the time concerning nuclear power, it is not to be taken as what was actually considered a realistic cost estimate.

critical attention as well as urgency for HLW management. So despite other options at least being investigated, ERDA continued the AEC's quest for the expansion of GD with the National Waste Terminal Storage (NWTS) Program in the latter half of the 1970's, wanting to build six repositories by 2000. In light of these developments, however, that period also saw increased critical input from geologists and physicists on GD's feasibility. The optimism that generally governed the AEC's attitude towards GD now met with more critical inquiry, which was reflected in the Interagency Review Group on Nuclear Waste Management's (1978) report to the US president. The report acknowledged that knowledge, experience and predictive capability on repository operation was lacking. And while it still strongly recommended proceeding with GD, it also advised using a "technically conservative" approach (e.g., p.46), which includes *reversibility* of waste emplacement decisions (p.18) and temporary *retrievability* of emplaced high-level waste during an initial period of repository operation (e.g., p. 46)[152]. Other developments helped increase the USA's dependence on GD, as the closed fuel cycle that the AEC had pushed for two decades was plagued with even more difficulties. While the newly-founded NRC was investigating the proliferation concerns connected to plutonium recycling and the safeguards necessary to make it work in 1975-'76 (which worried a nuclear energy industry that still favoured reprocessing), reprocessing received increased public attention (J. S. Walker 2009). This escalated when reprocessing became a prominent theme in the presidential race between President Ford and Jimmy Carter, in which both eventually expressed reservations with regards to the appropriateness of reprocessing SNF. After Carter became president, he issued a statement (Carter 1977) that the USA would "defer indefinitely the commercial reprocessing and recycling of the plutonium produced in the U.S. nuclear power programs", and that "a viable and economic nuclear power program can be sustained without such reprocessing and recycling". Official policy turned against reprocessing and the Barnwell reprocessing facility was mothballed and never came online, which effectively meant the end of the civil reprocessing industry[153]. So not only was GD the only technology of the AEC's old program

[152] Note that the NEA's R-scale (OECD Nuclear Energy Agency 2011) provides a specific timeline and a more gradual decline of retrievability than does the IRG, and is more operationalized.

[153] Although the Reagan administration withdrew the ban on reprocessing in 1981 (U.S. Congress Office of Technology Assessment 1985), it never became part of official U.S. radioactive waste policy again.

that had any promise of becoming a reality, but without reprocessing of SNF the U.S. nuclear fuel cycle would generate larger quantities of high-level waste that remain radioactive for significantly longer than in a fuel cycle with such reprocessing (Taebi and Kloosterman 2008), since it would have to dispose of unprocessed SNF. As such, it became even more critical to look for high-level waste management technologies that were focused on maximal long-term safety, something GD was already known for. From this point on, there was little question as to which technology would be best for the management of high-level waste (as it was in the mid-1970's (e.g., U.S. Atomic Energy Commission 1974)), despite the fact that not reprocessing SNF put more severe demands on repository design and siting.

Implementation of GD still proved difficult though, as the search for possible sites in light of the NWTS met with many negative reactions from state executives and lacked permissions for exploration. Combined with federal budget cuts, this forced the geological disposal program to forego the desired expansion. Nevertheless, efforts to operationalize GD continued. Shortly after the publication of the abovementioned IRG report, the DOE (formerly ERDA) published its Generic Environmental Impact Statement on Commercial Radioactive Waste Management in 1980, which was intended to support a programmatic decision to focus efforts on mined GD (Metlay 1985). Around the same time, the NRC was working on its proposal for the technical criteria that should govern repository licensing[154], also focussing on GD as the standard solution (J. S. Walker 2009). This coalescence of institutional efforts towards the implementation of GD was subsequently expressed in the 1982 Nuclear Waste Policy Act (NWPA), which followed the DOE's and the NRC's commitment to mined geological disposal. Moreover, the act added even more urgency into the equation by aiming for repositories to be operational by 1998 (and capable of taking unprocessed SNF), and shifting some focus away from Monitored Retrievable Storage[155] (MRS, similar to the AEC's Retrievable Surface Storage Facilities),

154 These criteria included many concepts still visible in the NEA's proposal today, like multiple barriers, the validation of models, geological uncertainties, and the problem of human intrusion (Metlay 1985).

155 While industry favoured MRS as a temporary solution, environmental groups again protested it out of fear of MRS facilities becoming *de facto* permanent disposal sites. The NWPA only foresaw inquiry into the need for and feasibility of MRS, but did not order any concrete construction (Vandenbosch & Vandenbosch 2007).

saying it was not a complete alternative to GD (Vandenbosch & Vandenbosch 2007). On top of all this, the government would provide only limited support for temporary storage as it could be perceived as a reason to delay final disposal efforts. Following the establishment of the 1982 NWPA, nine sites were selected as possible candidates for repository construction. In the following years, a complex process of negotiations narrowed this list down to three: Hanford, Washington; Deaf Smith County, Texas; and Yucca Mountain, Nevada. However, partly driven by political and cost considerations, the search was even further narrowed down in the 1987 Nuclear Waste Policy Amendments Act, limiting site characterization efforts to Yucca Mountain, Nevada only.

Yucca Mountain's history is interesting in its own right[156], as it has been central to decades of struggle to construct a working GD facility. However, I think it unnecessary to elaborate on it here, for two reasons. Firstly, the analysis as presented above contains the necessary elements for explaining GD's rise to dominance and why it could be difficult to do otherwise (see section 5.3.4). Further describing the case of Yucca Mountain and the policy-making around it would not take the analysis in a significantly different direction. Secondly, the case of Yucca Mountain and the adherence to GD even after Yucca's failure arguably serves better as evidence for GD's tenacity rather than as an explanation for it (aside from increased commitment and added urgency factors which were certainly not absent before). Indeed, due to significant technical as well as social and political hurdles, Yucca Mountain never became the USA's first non-military GD site. In 2011, the Obama administration even gave up further efforts to make it into a working disposal site for SNF, as such eliminating hope of having an operational repository in the near future. However, in spite of a history riddled with difficulties (of which three decades revolved around Yucca Mountain), GD remains the go-to option for high-level waste management in the USA (e.g., Blue Ribbon Commission on America's Nuclear Future 2012).

5.3.4. Is Geological Disposal Locked-in?

After all this, is GD locked-in in the USA? Let me start by discussing two objections to the idea that this is even possible, or that we can know that it is so.

156 For a comprehensive overview of the policy and technical difficulties in SNF management in this period, see Vandenbosch & Vandenbosch (2007) and Macfarlane & Ewing (2006).

First, one could question how it could be possible for GD to be locked-in if it seems incapable of actual implementation, even after decades of effort. However, as argued in section 5.3.1, if symbolic and institutional micro-irreversibilities are sufficient to drive actors to continuously commit to a specific technology, this could be all that is necessary for that technology to be locked-in. At least, it could be enough to make the process of technology development and implementation inflexible in terms of the practical possibility of changing its course, i.e., path-dependent. In other words, having many material manifestations does not make a technology irreversible; having the relevant actors repeatedly orienting their actions towards making that technology (even more of) a reality does[157]. The way this worked out in the case of GD is summarized below.

Second, can we know if GD is locked-in if no 'realistic' alternatives are currently available to which one could switch? After all, in many famous (albeit not uncontroversial) cases of path dependence and lock-in, equally good or even better alternatives were available but not being selected, for example with VHS tapes (Arthur 1990), the QWERTY keyboard (David 1985), or PWR reactors (Cowan 1990). Would most actors still commit to GD if a better solution was available? Unfortunately, this is a counterfactual that is impossible to prove. As such, it would seem at first glance that any claim that GD is irreversible can only be trivially true, i.e., it is impossible to switch to an alternative as long as there are none. This, however, neglects three factors. One, what counts as an equally good or better alternative is not set in stone. That safety and containment have long been leading in the judgment that GD is the only realistic path to follow is to some extent historically and politically contingent. Two, it is possible to add plausibility to the claim that GD is locked-in by showing that its history exhibits characteristics of a path-dependent process, i.e., micro-irreversibilities driving increasing returns in favour of GD, leading up to a point at which it is difficult to do something other than GD. Three, the fact that no realistic alternatives are available at this point in time partially follows from the very historical develop-

157 First, note that having many material manifestations can indirectly increase lock-in, since it allows for learning effects, economies of scale, sunk costs, etc., all of which can push actors to commit to the technology, i.e., constitute increasing returns. Secondly, this means that one should not ask whether it is *either* high-level waste policy practice *or* the technology of GD that is irreversible, since policy maker's continuous commitment could theoretically be sufficient to make GD locked-in.

ments that lead to GD's dominance. All three factors are discussed in this section.

Already gaining salience during GD's genesis before 1957 and inspired by the post-WW2 period, the themes of safety and containment have since guided the management of HLW and SNF. As such, these themes have been increasingly embodied materially (e.g., solidification of liquid HLW, multi-layered storage containers, and of course, the technology that is GD) and institutionally (e.g., the separation of the military and civil nuclear energy program, Carter's decision to refrain from reprocessing to contain the atom's proliferations risks, the urgency in the NWTS and NWPA for curtailing above-ground SNF build-up and continuous institutional commitment to GD as a way of doing so). In turn, these embodiments have helped reinforce and operationalize safety and containment as leading values. As such, the adoption and continuous reaffirmation of these values functioned as symbolic micro-irreversibilities that supported the path of GD as an appropriate solution for HLW and later, SNF[158].

As GD's story unfolded after its contingent starting period (1944-1957), an accumulation of micro-irreversibilities occurred favouring GD. These, combined with broader societal developments, have repeatedly helped drive actors to adhere to GD as the final solution for HLW and SNF. Indeed, after the themes of safety and containment gained prominence and the 1957 Committee on Waste Disposal report proposed GD as the most promising method for making them a technological reality, GD received the institutional commitment of both the AEC and the industry (albeit in combination with reprocessing of SNF). GD was now embedded as an essential part of policy for future HLW management. During the 1960's, serious research into GD (including small-scale test sites) acknowledged its feasibility as well as increased its lead compared to alternatives, which were not systematically looked into since optimism concerning GD's appropriateness and feasibility was wide-spread. However, as GD came closer to real implementation it ran into difficulties (exemplified by the failure at Lyons, Kansas), as did the organisation responsible for it: the AEC. The AEC was

158 This is in no way supposed to be a polemic against considerations of safety. However, in light of a demand for reversibility, even these value judgements should be open for reconsideration, since other values might prescribe other solutions. For example, an assessment based on maximizing future generation's opportunities for making use of SNF (something the NEA mentions as one of its reasons for reversibility in GD), would likely select a different solution than GD.

disbanded out of worry about the conflict of interest it operated upon, and alternatives for GD were more systematically investigated. However, several factors kept GD on its dominant course. Firstly, while actors were more critical of GD during this time, the value system behind its selection was not under similar scrutiny. Secondly, the pressure on the nuclear energy program to urgently provide solutions was significantly increased by a number of factors: the end of reprocessing and the fact that now SNF needed to be disposed of, Carter's strong political stance on the dangers of proliferation combined with increasing SNF build-up, increased societal displeasure with the nuclear energy industry, and the failure to implement a temporary arrangement in the form of the Retrievable Surface Storage Facility. It is unsurprising, then, that the response to critical inquiry into GD in the late 1970's actually was greater commitment to GD under an increased sense of urgency. Like when PWRs were selected for power generation (Cowan 1990), urgency can be an important driver for conservatism in technology selection. What was needed was a technology with which there was considerable experience, even if there may have been alternative technologies for the job eligible for (further) development. Thirdly, ERDA continued the AEC's quest for expansion of the GD program, assuring continuity of institutional commitment. As a result of all this, GD survived its minor 1970's crisis. After this point, GD's practicability (with increased knowledge, experience, and increasingly structured institutional frameworks) and political legitimacy (with the explicit commitment to GD in the 1982 NWPA) further increased, as such making it even more into the 'realistic' solution it is still taken to be.

In addition to these mechanisms supporting GD, there were also reasons why alternative paths were specifically not selected. For example, in a situation of limited resources available for organizing high-level waste management (especially at a time when the focus was on developing the energy industry rather than on ways to manage its wastes properly), it is clear that commitment to GD would mean even more limited resources available for development of possible alternatives, especially when it is assumed that there is little reason to do so. Indeed, until the mid-1970's, the AEC and the industry saw little need to systematically look into and develop alternatives to reprocessing and GD. Some possible alternatives, like disposal in the seabed or under Arctic ice sheets, would have also been unpopular both with an increasingly environmentally aware public in the 1970's as well as other countries across the world. Also, further development of more advanced fuel cycles that would reduce waste lifetime (and as such, lessen demands on disposal technologies) were incompatible with the ban on reprocessing in 1977 as they were judged to give rise to unacceptable proliferation concerns.

After all this, the case of Yucca Mountain, its failure, and the subsequent retention of GD as the most favourable solution for high-level waste disposal attests to the fact that a point has been reached at which switching to an alternative solution for high-level waste management has become difficult (not least because possible alternatives, other than temporary storage, are underdeveloped). Still, this is quite peculiar given the lack of working civil GD sites in the USA[159]. Apparently, it can become extremely difficult to change course on the choice for a specific technological solution despite extremely few actual working instances of the technology itself.

Finally, allow me to briefly elaborate on the evolution of reversibility considerations in GD over the course of its history. It is interesting that while the National Research Council's 1957 report contends that HLW should be emplaced in geological repositories without concern for its retrieval, the 1979 IRG report features provisions for limited retrievability on the basis of epistemic and prudential considerations. This was both politically salient as well as in line with the critical appraisal of GD in the late 1970's. And while the NEA's *reasons* for retrievability presented in section 5.2 have significantly expanded in scope to considerations of justice when compared to the IRG's, the *practical* side of reversibility and retrievability does not seem to have followed suit. Indeed, while the reasons for reversibility considerations have significantly evolved, our choice and design of the technology meant to fulfil these has not sufficiently done so, as evidenced by the discrepancies noted in section 5.2. On the one hand, if GD is locked-in, this could possibly help to explain why these discrepancies exist between the NEA's reasons for reversibility and retrievability and the extent to which GD seems to be an appropriate means of achieving them, since it would be extremely difficult to change to a solution more in line with new reasons for wanting reversibility. On the other hand, the inclusion of reversibility and retrievability considerations in GD does not seem to have lessened its dominance. *Au contraire*, making GD compatible with increased demands on high-level waste management (be it epistemic demands (IRG) and/or demands for

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159 For HLW from the military nuclear program, there is the Waste Isolation Pilot Plant (WIPP) in New Mexico which has been receiving waste since 1999, although its history since 1973 has also not been without both technical and socio-political difficulties.

justice (NEA)) would make it less pressing to work towards alternatives. So the inclusion of reversibility considerations, while lowering the probability of problems with GD arising, has not alleviated GD's lock-in.

The history of GD sketched above contains ample micro-irreversibilities that would lead GD to become locked-in by making it more likely that agents favour GD. By the same token, and partly due to the same developments that led to GD's dominance, alternatives have not been extensively pursued. So, in addition to GD being locked-in in a trivial sense (no 'realistic' alternatives are currently available), these factors provide plausibility to the idea that GD is locked-in due to being unable to shake free from its own history. As such, considering the first question put forward in section 5.2:

- Would an authorized body be reasonably able to switch from GD to an alternative solution if problems with GD were to arise?

, it seems that, at least for the USA, one would have to conclude that it would be at least difficult and at worst impossible for an authorized agency to step down from GD as the dominant high-level waste management technology, at least within a reasonable timeframe. Given that GD is the preferred solution to the high-level waste problem in most nuclear energy-producing countries[160], and that other countries do not have access to more alternatives to GD than the USA does, I think it not unreasonable to expect that in some of these countries, GD might be similarly locked-in[161].

If all the above holds true, GD at least partly fails to meet one of the conditions and can thus not be considered a truly reversible technology (in those specific cases). However, one could ask whether GD's lock-in is really problematic, given that a) scientific confidence in the capacity of engineered barriers and geology to contain high-level waste is significant, and b) that no technology is readily available on a satisfactory scale to turn high-level waste into benign substances? That is, is it not a good strategy for 'undoing' the morally undesir-

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160 One should not forget the impact of international organisation and cooperation. For example, given that the IAEA was set up in 1957 (pushed by the Eisenhower administration after the 1953 'Atoms for Peace' speech), one can imagine the subsequent international spread of the themes of containment and safety (e.g., IAEA, 1956).

161 However, even if this expectation is reasonable, any claim to a specific country having GD as a locked-in technology would have to be backed up by the necessary socio-historical analysis.

able consequences of nuclear energy technologies? This question relates directly to the second question put forward in section 5.2:

- Does GD exhaust the possibilities of undoing the consequences connected to high-level waste, and the hazards that could come about due to the use of GD for managing this waste?

In the following section, I contend that there are different general strategies for undoing such consequences that one can follow in developing a technology, and that some are preferable over others, at least *qua* reversibility. GD is principally focused on one of these strategies, albeit not the most preferable one.

5.4. On Geological Disposal's Capacity for Undoing Consequences

What does it mean to 'undo the consequences connected to high-level waste'? What would constitute an 'ideal' undoing of consequences is, practically speaking, impossible: one simply cannot go back in time and start over. Nevertheless, what sorts of action could one still undertake towards the undoing of consequences, limited as they may be? In what follows, I present four practical strategies for 'undoing consequences' in order of decreasing similarity to 'ideal' undoing:

1) *Remediation*: bringing (parts of) the system under consideration back to a previous state by eliminating the problem source and using (part of) the system's internal dynamics to undo the unwanted effects of the technology's development and implementation. This seems to require the least invasive effort, and leaves a solid basis for other developments.
2) *(Re)construction*: bringing (parts of) the system under consideration back to the state by eliminating the problem source and actively reconfiguring system parts to reconstruct the previous state so as to undo the unwanted effects of the technology's development and implementation.

Note that the previous two imply elimination of the problem source. In the case of RWM in general and of GD in particular, high-level waste would have to be considered the most important 'problem source', and this is what the rest of this section will focus on. Other possible problem sources might be specific institutional arrangements or possibly outdated value systems (i.e. institutional or symbolic elements mentioned as micro-irreversibilities above). Given this possibility, undoing certain consequences may be as 'simple' as reverting to a state in which multiple possible paths were open, i.e. getting rid of lock-in. However, there are two more strategies for undoing consequences, ones in which the problem source is not eliminated:

3) *Containment*: Containment of the problem source without eliminating it, shielding potential victims from its harmful effects.
4) *Compensation*: Compensate victims for the undesirable consequences of the technology development project when even containment not possible.

One important point to make about these strategies is that if one wants to reasonably ensure that these options are available when the need arises, the technology in question needs to be *designed* according to these strategies. Another point is that these strategies are not mutually exclusive, and will most likely have to be used in conjunction. Also, there is a preferable order to these approaches: what cannot be solved by remediation should be tackled by reconstruction, etc. In this way, the potential for undoing unwanted consequences is exhausted to the greatest possible extent. These insights do have their implications though, the most important of which is probably the following: already during the development of a technology, one should aim for remediable and reconstructible solutions rather than ones dependent on containment or compensation. From the point of view of reversibility, the latter are little more than 'end-of-pipe' solutions necessitated by our incapability to construct more reversible technologies by eliminating problem sources. The question is: which of these strategies does GD exemplify?

One could argue that GD is a technology based on remediation. After all, the internal dynamics of the system (radioactive decay) will eventually undo the unwanted effects connected to high-level waste. When, after thousands of years, the waste reaches the radiation level of natural uranium ore, would the situation not be remediated? Well, at least not in the way that remediation is meant here as a strategy for undoing consequences: remediation would have to include the elimination of the problem source, no active steps towards which are actually undertaken in GD. Charitably to GD, however, one could argue that our actions implementing GD now do eliminate high-level wastes eventually. However, can we then really say that our actions eliminate these wastes? High-level waste and the risks connected to it (while diminished through multiple engineered and natural barriers) exist as possibly problematic for an extended amount of time, one that far surpasses any example of institutionalized practice or organized action. As such, even on this charitable reading GD fails to eliminate the problem source within a timeframe that is relevant for a *practical* conception of remediation as a strategy for undoing consequences. As such, we cannot claim that GD is a remediation-based technology.

Despite appearances (it requires very specialized and scientifically advanced construction after all) GD is also not reconstruction-based for the same reason mentioned above: the high-level waste is just not eliminated quickly (or actively) enough. At most, it could be said that retrievability considerations in GD's design do allow for some reconstructive action in case unwanted effects do occur, whether these effects are connected to the dangers of radiotoxicity or intergenerational injustice. However, the limited timespan for which retrievability is envisioned, combined with its diminishing nature and the fact that while retrieval would remove the problem source from its location but not entirely eliminate it, leaves GD's potential for reconstruction rather limited.

In the end, GD corresponds largely to the *containment* strategy: despite limited retrievability provisions, containment is indeed the design goal of GD. Rather than actively eliminating the problem source, it is contained behind multiple barriers, e.g., the vitrification matrix, multi-layer canisters, the repository with its multiple engineered barriers and even stable geological layers. But this is not all. The 'containment' strategy is so pervasive in GD that even its institutional and symbolic orders were oriented towards containment, at least for a large part of GD's history. For example, technocratic elites have generally left little room for public participation in how high-level waste was to be handled[162], especially during the early decades of nuclear energy development. Additionally, by viewing this waste in terms of difficult-to-control and largely irreversible risks, legitimation of technical and passively safe solutions was assured (especially when combined with a general distrust of social solutions). In short: GD works towards containment all the way down, from the top echelons of nuclear policy making to hundreds of meters below the earth's surface.

In GD's defence, however, one might rightly bring up the point that eliminating high-level waste is currently practically impossible. No technology is actually

162 Given the difficulties to find public acceptance for waste storage sites or geological repositories, these processes have gradually opened up to some extent (Bergmans 2008; Richardson, Michie, Minhans, Kallenbach-Herbert, & Andersson 2011).

available to turn such waste into benign substances. Given this fact, is GD not the best technology available for taking our responsibility towards future generations? Two points need to be made in response to this. First, while it is true that no technology is currently able to 'eliminate' high-level waste, this does not mean such technologies are not at least realistic. For example, a process called partitioning and transmutation (P&T) is being developed which could theoretically decrease total high-level waste volume as well as limit its lifetime to as little as 500-1000 years (Condé, Andersson, Sandström, & Norby 2004). This would constitute at least a partial elimination of the problem source and as such, could be part of a reconstruction strategy to undo the unwanted effects of high-level waste. While a fuel cycle including P&T would be more expensive than using a more traditional fuel cycle, and comes with its own security and safety concerns, it would at least be a step up in terms of undoing unwanted consequences in the form of long-term risks of high-level waste radiotoxicity (Taebi & Kadak 2010). The second point to be made concerns the manner in which containment of high-level waste is achieved in GD: it prohibits or at least makes it incredibly arduous to switch to a more reversible strategy in the future due to a lack of retrievability. For example, by the time P&T would actually be available on a large enough scale to make a significant difference, repositories could be largely or completely closed. And even if retrievability was fully implemented and maintained, the possibility of reprocessing/recycling/destroying some high-level waste would prove difficult, e.g., due to being stabilized in glass or concrete. Indeed, it would seem that the epitome of containment entails closure, not only of repositories and institutional orders, but also closure of different options for switching strategies for undoing (the effects) of high-level waste.

Let me make two qualificatory notes. First, a reconstruction-based technology like P&T is not likely to become a complete replacement of GD, or the strategy it represents. With HLW that remains radioactive for 'only' a couple of thousands of years, decent containment would still be necessary. As such, the containment strategy still has a place in the management of high-level waste, but only insofar as reconstruction's potential has been exhausted first. Secondly, these new circumstances might open up options for the form a containment strategy/technology may take, possibly loosening the lock-in of GD as the dominant final solution for high-level waste management. However, P&T's infrastructural and institutional demands may institute their own path-dependent processes and possibly locked-in technologies, and have their own negative consequences other than long-term risks of radiotoxicity. In other words, optimizing one of the conditions for reversible technologies might entail losing out on the other. Moreover, since, the operationalization of the two conditions do not allow for a comparison on one similar measuring scale, balancing the two conditions would likely need a careful exercise in practical and/or political reason.

There is currently some attention for the role of *compensation* in RWM (e.g., Kojo, Richardson, Oksa and Mihók 2013). While not usually linked to the reversibility debate outside of a public demand for retrievability provisions, I hope that the four strategies presented provide a clue as to how compensation features in reversible GD. It is a possible strategy for achieving more capacity of undoing unwanted consequences, but only to be applied when the other three are sufficiently exhausted. Although there may be other principal and practical reasons like justice or social acceptance to resort to compensation outside of reversibility considerations, any claim to increased reversibility directly because of compensation should be treated with caution.

To conclude, it seems that the second reason (next to being significantly locked-in) that GD, even with reversibility provisions, apparently fails to meet the NEA's own justification of reversibility is that its strategy for undoing unwanted consequences is less-than-ideal for two reasons. Firstly, a remediation- or reconstruction-based technology would at least in principle be more able to live up to the NEA's justification of reversibility. Secondly, the way GD embodies containment is so severe that it disallows remediation or reconstruction of geologically disposed high-level waste at a point in the future at which these options would become viable.

5.5. Conclusion

At the start of this paper, the way reversibility features in GD was explored, and a number of critical discrepancies were noted between the reasons given for the inclusion of reversibility provisions in GD and GD's ability to live up to these reasons. This prompted the question whether GD could be considered a reversible technology, since such a reversible technology would arguably be able to fulfil the reasons given in section 5.2. It was then put forward that for GD to be considered reversible, two questions need to be answered affirmatively:

- Would an authorized body be reasonably able to switch from GD to an alternative solution if problems with GD were to arise?

- Does GD exhaust the possibilities of undoing the consequences connected to high-level waste, and the hazards that could come about due to the use of GD for managing this waste?

Considering the second question, it was found that GD's strategy for undoing high-level waste-related consequences was less-than-ideal, since it relies mainly on a strategy of containment rather than on eliminating the waste through reconstruction or remediation. And while it is true that no technology exists that embodies these more ideal strategies, the way GD's containment works makes switching to these strategies for existing wastes rather difficult. Still, if and when such a technology eventually becomes available, could we not simply switch to it? The answer to the first question gives us reason to worry about this possibility. It would appear that GD is currently locked-in in the USA and quite possibly in other countries that espouse GD as well. The historical process of GD's development and operationalization has brought us to a point where these societies' symbolic, institutional and material investment in GD makes it difficult and thus unlikely that GD will be replaced with an alternative any time soon. With *at least* one of the questions answered negatively the conclusion follows that despite laudable efforts to the contrary in the past decades, GD is currently a practically irreversible technology for RWM. Taking measures both to avoid lock-in situations as well as exhausting the (future) possibilities for reconstruction and remediation for undoing high-level waste-related consequences could be fruitful strategies for increasing RWM's reversibility. However, optimizing both of these conditions of technological reversibility might prove difficult with some technologies, since scenarios are imaginable in which solutions in favour of one of the conditions decrease the potential of the other. For example, the future introduction of P&T could improve the ability to undo high-level waste-related consequences (since it is a reconstruction-based technology) and even lessen the severity of GD's lock-in (if applicable). On the other hand, P&T relies on extensive and complex infrastructures which could themselves become locked-in and have their own undesirable consequences. This creates an additional difficulty for finding truly reversible technologies or for balancing the two aspects in a way that is satisfactory, since an affirmative answer to both questions is necessary to truly speak of technological reversibility.

Of course, it must be remembered that this paper is focussed specifically on reversibility. However, when deciding on the specific form an RWM technology is supposed to take, or even which one(s) to select, more values are bound to be eligible for serious consideration. Indeed, issues of safety, justice, feasibility, efficiency, etc. also need to be considered, and might turn out to be partly incommensurable with a technology's reversibility. As such, this paper is not meant as a plea for the sole consideration of reversibility in the GD debate. Rather, it provides a clarification of what technological reversibility entails and how it is to be achieved, which is essential if reversibility is to be considered next to other important values.

What does all this mean for the hypothetical experimenter the paper opened with? After all, if she is to be prepared for learning that the experiment is to be stopped, the technology she is experimenting with should be reversible. If the analysis presented in this paper is correct, reversibility can only be ensured by its proactive consideration, both in designing the nuclear energy technology in question (according to strategies for undoing undesirable consequences) as well as keeping alternative solutions viable and avoiding disproportionate institutional and symbolic commitment (avoiding lock-in). This would mean that GD's lock-in as well as its less-than-ideal prioritization of the containment strategy require careful revision. As it stands, however, the inclusion of reversibility in GD by the NEA is hardly adequate to the reasons provided for it, let alone to the standards of properly reversible experiments with RWM technology.

Lastly, to what extent do the results of this case-specific analysis carry over to the general framework of social experimentation with new technologies? While the recommendations for avoiding lock-in could work for other technologies due to their generality, the strategies for undoing consequences might need reconsideration. That is, some technologies may have different options for undoing consequences which invite different strategies for doing so, although this would have to be determined on a case-by-case basis. The original phrase by van de Poel "containment of hazards as far as reasonably possible" (2011 p. 289) turns out to be overly specific in this regard, since containment is just one possible strategy for undoing undesirable consequences. It must be noted, however, that responsible social experimentation demands more of a responsible experiment than it simply being reversible (van de Poel 2011). So, while (some) reversibility might be a necessary condition of responsible experimentation, it is by no means sufficient.

6 Conclusions

This thesis set out to conceptualize and explore the notion of reversibility with regards to nuclear energy technologies. In doing so, it aimed to answer the following research question and corresponding subquestions:

RQ: *What are the implications of reversibility for the responsible development and implementation of nuclear energy technologies?*

SQ1: *Under what conditions can nuclear energy technologies be considered reversible?*
SQ2: *Why should nuclear energy technologies be reversible?*
SQ3: *If so, how could the reversibility of nuclear energy technologies be achieved?*

This chapter first summarizes the central findings of the thesis and how these help to answer the subquestions, after which it reflects on the complications and implications of reversibility considerations for the development and implementation of nuclear energy technologies. Next, it presents an answer to the main research question. Finally, it reflects upon the extent to which the results of this work can be further generalized and identifies some of their limitations.

6.1. Subquestion 1: Under what conditions can nuclear energy technologies be considered reversible?

The first subquestion asked under what conditions nuclear energy technologies can be considered reversible. To come to these conditions, a *conceptualization of technological (ir)reversibility* had to be developed that is a) suitable to the notion of social experimentation with nuclear energy technologies, which, as chapter 5 shows, current approaches to reversibility in nuclear energy policy fail to do adequately, and b) can do justice to the importance of institutional, political and symbolic aspects of national nuclear histories, which many theoretical approaches to technological (ir)reversibility insufficiently incorporate.

Building on Giddens' theory of structuration and Orlikowski's work on the duality of technology, chapter 2 conceptualized technology development as a process of structuration of human aspirations, in which reflexive agents transform the world by introducing, reproducing and transforming technologies that consist of material, institutional and symbolic structural elements. According to this conception, technologies become *irreversible* when their constitutive elements become caught in circuits of reproduction. These circuits of reproduction tend to persist when there is little to no disalignment between the material, institutional and symbolic elements of a technology and/or when there is a concentration of resources with those agents in support of the technology, since these factors lower the chance of successful disruptive events occurring. When disruptive events do occur, they can break the circuit of reproduction and/or undo the structural elements that make up the technology. When the circuit of reproduction is not broken, but some elements of the technology are nevertheless undone, the technology can be considered *partially reversed*.

The applicability of this theoretical lens to the case of nuclear energy technologies was subsequently demonstrated by applying it three historical cases of nuclear energy technology development, i.e., in India, France and the USA.

Based on these insights, two general conditions for the reversibility of nuclear energy technologies were proposed, both of which should be fulfilled if such a technology is to be considered fully reversible:

1) The ability to stop the further development and deployment of a nuclear energy technology in society.
2) The ability to undo the undesirable outcomes of the development and deployment of that nuclear energy technology.

Two main features of the structurational conceptualization of (ir)reversibility provided inspiration for these conditions. First, the disruption of the circuit of reproduction is represented by the first condition and the undoing of the technology's structural elements in the second one. Secondly, rather than defining reversibility as a feature of the technology, the conditions do so in terms of *agency* that, according to the framework, is constituted by the structures in which agents find themselves (technological or otherwise). As a consequence, reversibility becomes context-dependent, and the same material technological artefacts or systems may have different degrees of reversibility in different cultural, institutional and infrastructural contexts.

6.2. Subquestion 2: Why should nuclear energy technologies be reversible?

The second subquestion of this thesis was concerned with *why* nuclear energy technologies should be reversible, irrespective of whether they are considered experimental. The Levinasian analysis of the relation between responsibility and innovation in chapter 3 provided support, albeit indirectly, for the position that reversibility is indeed desirable for the responsible development and implementation of nuclear energy technologies.

It established that, while our responsibility to others necessitates the development of technology, *it also establishes technology as necessarily provisional and in need of change*. It did so by structuring Emmanuel Levinas' ethical phenomenology into three mutually dependent 'stages', each described in terms of their leading experience and objectivation regime. This allowed for a more systematic appraisal of Levinas' episodic reflections on technology and clarified the relation of technology to other important Levinasian themes such as responsibility, justice and politics. This analysis showed that techno-politics (i.e., technology and politics), while necessary for concretely fulfilling our responsibilities to others, also inevitably falls short of the infinite responsibility that inspires it. Abating this ethical dilemma in techno-political practice requires an openness to the questioning Other, which concretely implies (among other things) the need for a *flexible technological set-up of the world* that allows for specific technologies' implementation to be stopped and their negative consequences to be undone. In short, it calls for technological reversibility.

As such, a Levinasian understanding of technology supports the idea of reversibility as a *general* requirement for technology. The desirability of reversibility for nuclear energy technologies would thus simply follow from the fact that they *are* technologies. This does not rule out, however, that there are specific reasons to pay additional attention to the reversibility of nuclear energy technologies. Their track record of irreversibility (see chapters 2 and 5), potential for catastrophe (e.g., in case of reactor meltdown), effects on the openness of politics (their authoritarian tendencies do not sit well with Levinasian techno-politics), the potential harmful effects of their waste products on future others who cannot speak for themselves, and the large investment costs and infrastructural needs involved all serve to increase the moral desirability of reversibility while also making reversibility exceptionally difficult to practically achieve. In light of this, the question of how nuclear energy technologies could be made reversible seems exceedingly pertinent.

6.3. Subquestion 3: How could the reversibility of nuclear energy technologies be achieved?

Having argued above that nuclear energy technologies should be reversible, the third subquestion needs to be answered: how can reversibility of nuclear energy technologies be achieved? Basically, this boils down to fulfilling both of the conditions for technological reversibility formulated in response to the first subquestion: 1) the ability to stop the further development and deployment of a nuclear energy technology in society, and 2) the ability to undo the undesirable outcomes of the development and deployment of that nuclear energy technology. The insights in this thesis on *how* these conditions can be fulfilled have been developed based on existing theory and case studies of nuclear energy technology development and implementation. However, *given nuclear energy technologies' propensity for irreversibility,* it was surmised that fulfilling the conditions for reversibility first and foremost implies a need for strategies that help to avoid such irreversibility. Therefore, rather than studying cases in which nuclear energy was successfully abandoned, the focus in this thesis was on nuclear energy development trajectories that have proven to be more or less irreversible. That is, the approach to answering the third subquestion was to first understand how nuclear energy technologies become irreversible, which subsequently inspired strategies to help avoid such an outcome. In what follows, the insights thus developed are presented separately for each condition for technological reversibility.

6.3.1. Fulfilling the first condition for the reversibility of nuclear energy technologies

The first condition for the reversibility of nuclear energy technologies is concerned with the ability to stop the further development and deployment of such a technology in society. However, this ability can become severely hampered when technologies and their adoption in society exhibit certain characteristics. These characteristics were further explored in chapters 2, 4 and 5.

Based on a structurational understanding of technology development, chapter 2 theorized that it becomes increasingly difficult to reverse the development and deployment of a technology if it gets 'caught' in circuits of reproduction. That is, when reproduction of the technology (which consists of *material*, *institutional* and *symbolic* elements) by reflexive agents exhibits positive feedback, the technology and its embedding in society become increasingly stable and difficult to overcome. Two specific factors were identified as contributing to the likelihood of the continuation of circuits of technology reproduction (and thus, making it more difficult to disrupt them):

- a lack of disalignment between the symbolic, institutional and material elements of a technology. There is disalignment between two such elements if reproducing one would weaken the other.
- the asymmetrical distribution of discursive, authoritative and allocative resources in favor of those who support the technology. Powerful agents in favor of the technology can more easily introduce and reproduce elements, but also have the resources to prevent others from acting upon disalignments (e.g. through secrecy or sanctions) or limit the effectiveness of such counter-efforts (e.g., by virtue of their influence on actual decision-making processes).

This framework was then applied to historical cases of nuclear energy development in India, France and the USA, which served to show how these theoretical insights play out in practice.

Nuclear energy development in India provided a case in which a lack of disalignment between the elements of nuclear energy technologies, combined with large discrepancies in resource distributions, kept the circuits of nuclear energy technology reproduction going. That is, in India, the symbolic connection of nuclear energy technologies to national pride, indigenous development and post-colonial independence was compatible with centralized technocratic governance and faith in government policy decisions. This provided legitimacy to long-term planning of nuclear energy technology development and implementation (Homi Bhabha's three-phase plan), ensuring that little disalignment between symbolic, institutional and material elements could arise. Institutional resources were concentrated with the DAE and the Prime Minister, thus centralizing decision-making on nuclear development. This concentration of resources was further safeguarded by discouraging foreign players to enter the Indian nuclear energy market. Finally, stringent secrecy further deprived possible opponents of the nuclear regime of discursive resources, lowering the chance and effectiveness of opposition. As such, the strength of specific symbolic and institutional elements as well as large discrepancies in resource availability in favor of those supporting the nuclear program were sufficient to continue India's circuits of reproduction.

In the USA, on the other hand, the circuit of reproduction was actually broken based on increasing disalignment between the elements of the USA's nuclear energy technologies and increasing institutional and discursive resources for opponents. First, there was a disalignment between promises of cheap nuclear energy and safe nuclear energy, since regulations that were meant to increase safety also significantly increased costs. Secondly, there was a disalignment between those increasing costs of nuclear energy on the one hand, and the goal of creating a competitive and privatized nuclear energy industry on the other. Around the same time that these disalignments were growing, the dissolution of the AEC and the assumption of its responsibilities by the NRC and ERDA constituted a significant change in the institutional set-up of the USA's nuclear energy program. This, combined with increased opportunities for legal contestation (mainly based on new environmental legislation) and the limited secrecy necessitated by a privatized nuclear energy industry, provided institutional and discursive resources to opponents who could now act upon the above-mentioned disalignments and thus effectively oppose nuclear new-build. These factors made nuclear energy less attractive to private investors, which led to nuclear energy expansion in the USA grinding to a halt by the end of the 1970's, breaking the circuit of reproduction of nuclear energy technologies in the USA.

Lastly, the case of French nuclear energy technology development was interesting because it provided an example of what I have termed *partial reversibility*. This means that its circuit of reproduction was *not* broken, but a limited set of structural elements of France's nuclear energy technologies were nevertheless replaced in the 1960's and 1970's (see table 2.4). Specifically, the introduction of new symbolic elements like the 'competitive kilowatt-hour' and the conceptual separation of nuclear energy production from other nuclear applications created disalignments with other elements of French nuclear energy technologies (such as the CEA's focus on plutonium production), which made it possible for EDF to wrest authority over power plant construction and operation from the CEA. This constituted a significant change in the institutional elements of French nuclear energy technology. It provided EDF with the discursive and institutional resources necessary to change some of the dominant material elements of French nuclear energy, i.e., making the PWR reactor (which was optimized for energy production) the dominant reactor type instead of the CEA's UNGG reactors.

Based on these theoretical and empirical insights, chapter 2 provided two general strategies for fulfilling the first condition for technological reversibility. That is, increasing the ability to stop the further development and deployment of nuclear energy technologies in society (i.e., to break their circuits of reproduction) involves:

1) avoiding excessive resource asymmetries between agents, and
2) ensuring the possibility of introducing novel symbolic, institutional or material elements.

This would for disalignments between structural elements and opens avenues for disruptive action. With this, chapter 2 provided quite general strategies for *overcoming* technological irreversibility by disrupting circuits of technology reproduction. It did not, however, provide much insight into how technologies get 'caught' in these circuits of reproduction in the first place. Moreover, it provides little insights into *why* agents reproduce a technology and the specific economic, political or other mechanisms that drive those adoption decisions.

To find out how technologies initially get caught in circuits of reproduction, why agents adopt them and how those adoption decisions make those technologies more irreversible, chapter 4 looked deeper into another, compatible theoretical framework that explains the lock-in of technologies on the basis of positive feedback: technological path dependence.

The theory of technological path dependence was explored through the phenomenological lens of Alfred Schutz. It provided a phenomenological description of technology adoption, technology and the social environment in which it occurs. Technology adoption, understood in terms of subjective processes of choosing and acting, was seen as driving the positive feedback mechanisms in path dependent processes. In other words, mechanisms like economies of scale, learning effects and network externalities operate by virtue of technology adoption increasing the chance that that technology will be adopted again in the future (or lowering the chance that alternatives are selected). According to this analysis, the difficulty of stopping the further deployment of a technology in society and of switching to an alternative is an emergent outcome of numerous individual technology adoption decisions. The conceptual resources developed in the phenomenological descriptions of technology adoption, technology and the social selection environment were subsequently connected to utilitarian, functional, legitimacy and power explanations for path reinforcement. This provided insight into the reasons why certain technologies get increasingly adopted over alternative solutions[163], and how power asymmetries can determine others' technology adoption decisions.

This Schutzian rendition of technological path dependence is largely compatible with the notion of 'circuits of reproduction' of a technology described in chapter 2, since both describe processes of increasing technological inflexibility based on positive feedback and both assume a structurational notion of agency, i.e. iterational, projective and practical-evaluative (see section 4.2). Moreover, the subjective processes of 'choosing' and 'deciding' that form the basis of technology adoption correspond to Giddens' more encompassing notion of 'reflexive monitoring of action' (see fig 2.1), and chapter 2's 'aspirations' correspond to Schutz' notion of interests and plans as motivational relevances in technology adoption decisions. Moreover, the notion of 'negative adoption' can be seen as an important source of chapter 2's 'disruptive events'.

What chapter 4 adds to chapter 2 are insights concerning the subjective processes behind the circuits of technology reproduction (in terms of choosing and acting and how these link to technology adoption), the mediating role of technological, social and plan hierarchies, and the differentiation between utilitarian, functional, legitimacy and power explanations for increasing technological irreversibility. Of the latter, power explanations are of special interest here, since they further specify the idea that resource asymmetries contribute to positive feedback by identifying the most important ways in which they do so: by a) allowing powerful agents to influence the social stock of knowledge (e.g., through propaganda or secrecy) and b) enrolling others into the social hierarchies connected to a technology.

Interestingly, all four types of explanations for path reinforcement can be recognized in the cases described in chapter 2. First, *utilitarian explanations* for

163 In the case of nuclear energy technologies, alternatives could include alternative parts for the current technology, other nuclear energy technologies (see the case of France in chapter 2) or non-nuclear technologies that fulfil the same function. However, as chapter 4's discussion of functional explanations indicates, the function according to which another technology is an alternative need not necessarily (only) be energy production, although the latter would probably be the most likely scenario.

path reinforcement are most straight-forwardly recognizable in the USA case. There, increased adoption of nuclear energy technologies (and PWRs in particular) not only made it possible to improve these technologies, but also decreased the capacities necessary for future adoption due to experience gained by previous users (i.e., learning-by-doing (Cowan, 1990)). More importantly, however, increased adoption was also expected to greatly decrease costs and increase profits (however optimistic those expectations were), increasing both the extent to which financial interests were expected to be fulfilled but also increasing the plausibility of project success (i.e., learning-about-payoffs (ibid.)). These dynamics helped fuel the nuclear expansion described in chapter 2. Secondly, *functional explanations* were probably most evidently embodied in the case of India. An important reason for India to adopt an indigenous PHWR reactor type was not primarily that it excelled at efficiently producing energy, but rather that it fulfilled a function in *other* projects than simply energy production. These projects included military developments, energy independence (through the three-phase plan), and cultivating indigenous industrial and engineering capacities. Third, *legitimacy explanations* could be seen at work in the case of France, where the positive adoption of nuclear energy as well as avoiding its negative adoption were reinforced by the legitimacy it received from its role in the 'right and proper' project of restoring the radiance of France. Lastly, given the prominent role of governmental institutions in the national nuclear histories discussed, it is not surprising to find elements of *power explanations* in each of them. For example, in the USA, the authority of nuclear elites in the industry and the AEC lent credibility to each other's price projections (and also allowed them to define what was to be considered 'safe'), leading to nuclear expansion. In France, the CEA enrolled patriotic French citizens into (the plan and social hierarchies connected to) its nuclear energy project to rebuild the Radiance of France, if only by having them not standing in the way of progress. In the Indian case, stringent secrecy avoided negative adoption of nuclear energy technology by depriving potential opponents of discursive resources.

In addition to the above, the theory of technological path dependence also provides an explanation for how technologies initially get 'caught' in circuits of reproduction, a problem not addressed in chapter 2. When one technology gains a small early lead vis-à-vis competing technologies due to 'small historical events' (whether contingent or strategic in origin), this may set history on a new technological path. This path can then get further amplified by positive feedback mechanisms based on utilitarian, functional, legitimacy and/or power considerations, which may eventually lead to the technology being locked-in.

To probe the usefulness of this notion of path dependence (and lock-in) in determining whether the first condition for reversibility is fulfilled for a nuclear energy technology, it was applied in chapter 5 to the case of geological disposal (GD) of high-level radioactive waste (HLW) in the USA. Focusing on the cumulative effect of quasi-irreversible investments involved in decisions to adopt GD, it showed how alternative solutions to the HLW problem (disposal in the seabed or in ice sheets, extraterrestrial disposal, transmutation, etc.) became comparatively less well developed and less attractive the more GD was adopted. As such, in part due to its own particular history (see section 5.3), GD came to be seen as the only 'realistic' option available. At that point, an authorized body could not reasonably be expected to turn away from GD since it was locked-in. On this basis, it was concluded that the first condition for technological reversibility was not fulfilled in the case of GD in the USA.

On top of demonstrating the usefulness of path dependence for the purposes of this dissertation, this analysis showed how a technology can be locked-in by overwhelming commitment from relevant stakeholders, even when little to no working examples of the technology are present. This emphasizes the importance of the notion of aspirations (chapter 2) and of the possibility of adopting a technology as a future prospect (chapter 4). Moreover, it reiterates the importance of commitment to the symbolic and institutional elements that result from technology development (chapter 2) for the course of technological trajectories, e.g., in terms of the leading values of safety and security, and of embedding of GD in research programs, regulations, policy acts, etc.

Taken together, chapters 2, 4 and 5 provide an explanation for why the first condition for technological reversibility, i.e., the ability to stop the further development and deployment of a nuclear energy technology in society, might be difficult to fulfil. This is likely to be difficult because nuclear energy technologies can easily get locked-in or caught in circuits of reproduction. As such, fulfilling the first condition involves concrete efforts to avoid lock-in. Based on the above, such efforts would at the very least include[164]:

- *Keeping other technological options available and viable.* As the case of geological disposal in chapter 5 shows, changing to an alternative technology becomes incredibly difficult when the alternatives are significantly underdeveloped.
- *Avoiding asymmetrical resource distributions in favour of those who support the dominant technology.* This is especially pertinent in terms of knowledge and legitimacy production and enrolling others into social hierarchies. See, for example, the AEC's conflict of interest in the USA or France's connection of nuclear energy to patriotism, both in chapter 2.
- *Keeping commitment to specific values and other symbolic elements flexible.* For example, the early value commitments to safety and containment in the USA's HLW and SNF management policy played a significant role in GD's eventual lock-in (see chapter 5).
- *Ensuring possibilities for criticism of the technology by avoiding secrecy and including policy outsiders in the technology development and implementation process.* This helps to avoid overly asymmetric resource distributions and improves the chances for disruptive events. Furthermore, there is normative support for this strategy in terms of chapter 3's Levinasian technopolitics.
- *Creating space for the creation and dissemination of novel discourse about the technology.* For an example, see how EDF managed when it redirected discourse about French nuclear energy technologies away from explicitly political and towards more 'neutral' economic justification.

6.3.2. Fulfilling the second condition for the reversibility of nuclear energy technologies

Although this dissertation has mainly focused on the first condition for technological reversibility, chapter 5 also presented a number of *possible strategies to help fulfil the second condition*, i.e., the ability to undo the undesirable consequences of

[164] This list is by no means exhaustive. It is merely meant to show the types of concrete strategies that one could induce from the combined insights from chapters 2, 4 and 5.

a nuclear energy technology's development and deployment. It focused specifically on the most notorious undesirable material consequence of nuclear energy technologies: the very real risks connected to HLW and SNF, including illness and death due to exposure to radiation or ingestion of radioisotopes. In order to assess the extent to which GD can fulfil the second condition for reversibility, four possible strategies were presented for 'undoing' undesirable consequences. In *descending order of reversibility*[165], these were:

1) *Remediation*: bringing (parts of) the system under consideration back to a previous state by eliminating the problem source and using (part of) the system's internal dynamics to undo the unwanted effects of the technology's development and implementation.
2) *(Re)construction*: bringing (parts of) the system under consideration back to the state by eliminating the problem source and actively reconfiguring system parts to reconstruct the previous state to undo the unwanted effects of the technology's development and implementation.
3) *Containment*: Containment of the problem source without eliminating it, shielding potential victims from its harmful effects.
4) *Compensation*: Compensate victims for the undesirable consequences of the technology development project when even containment not possible.

It was concluded that, since GD focuses on the containment strategy rather than on reconstruction (either through partitioning and transmutation (P&T) or by ensuring long-term retrievability), it did not fully exhaust the possibilities of undoing the risks connected to high-level waste. Hence, it did not fulfil the second condition for technological reversibility to the fullest and could not be considered completely reversible. Generally speaking, the more the possibilities for remediation and reconstruction are exhausted before relying on containment or compensation, the more the second condition for technological reversibility is

165 See section 5.4. The ideal strategy for the 'undoing of consequences', i.e., simply going back in time and starting over, is impossible. However, the four strategies for undoing undesirable consequences presented in chapter 5 are meant to bring us closer to that ideal. Given that goal, strategies that also eliminate the problem source would be more reversible than those that do not because 'starting over' would imply that the problem source does not exist (yet).

fulfilled[166]. This can be done by taking remediation or reconstruction as guiding principles for designing the technology in question.

6.4. Complications of Reversibility Considerations: context-sensitivity and three dilemmas of reversibility

This dissertation has theorized what it means for nuclear energy technologies to be reversible, provided normative support for the position that their reversibility is desirable and presented strategies on how more reversibility could be achieved. It has, however, also identified a number of complications in requiring nuclear energy technologies to be reversible.

First, the formulation of the conditions already indicated that reversibility is not an inherent characteristic of technological artefacts but is rather constituted by the capabilities of agents, which in turn makes it heavily context-dependent. Given that this context is not static and co-evolves with the technology, however, efforts to ensure reversibility will at least need regular recalibration.

On top of this, both the progressive nature of path dependent processes as well as the 'descending order of reversibility' of the four strategies for undoing undesirable consequences (remediation, reconstruction, containment and compensation) indicate that technological reversibility is not an all-or-nothing affair. Rather, reversibility is a matter of degree, of technologies being more or less reversible. However, such an image of reversibility and irreversibility as the ends of a spectrum is further complicated by the fact that the two conditions for technological reversibility can be at odds with one another. That is, taking steps to fulfill one of the conditions for technological reversibility might decrease the ability to fulfill the other. One possible example of this is P&T being preferable to GD in terms of its strategy for undoing undesirable consequences, yet also running the risk of becoming at least as locked-in due to its large investment costs and complex infrastructural needs (see section 5.4). The possibility of the two conditions being at odds with each other represents the *internal* dilemma of the notion of technological reversibility presented in this thesis. It is important to note that reversibility is not the only consideration that can fall prey to such a

[166] One could of course argue that, if containment was guaranteed to work perfectly (which is doubtful in practice, if only due to the risk of human intrusion), then reconstruction would not be necessary. However, while both strategies may then be equally *safe*, they would still not be equally *reversible*.

dilemma. For example, adding safety systems to nuclear reactors can also add complexity, which could end up making the reactors more unsafe: the “paradox of safety systems” (Taebi & Kloosterman, 2015 p. 825). Along similar lines, the internal dilemma can be called the *reversibility paradox*.

In addition to the reversibility paradox, two more dilemmas haunt a call for more reversibility, one practical and one ethical. The *practical* dilemma of technological reversibility originates in the insight that some stability and reproduction of the set of structural elements of a technology is necessary for a technology to ‘work’. However, the more these elements are reproduced, the more irreversible the technology becomes. As such, the efficacy and reversibility of a technology may well be at odds. This has an important implication, i.e., while reversibility may be morally desirable, it is probably not *effective* to always maximize it. On top of this, the Levinasian analysis of technology in this dissertation also identified an *ethical* dilemma. That is, technology and the concomitant objectification of others is necessary for setting up the world in such a way that it can be used to help others in need, but it is unclear how technology’s capacity to do so is to be traded off against the need for openness of technology and politics to the Other (and the technological reversibility that implies). In other words, the question of how much technological reversibility is actually *desirable* is also dilemmatic, just like the problem of justice from which it sprang (see section 3.2.3).

In sum, technological reversibility is context-dependent and is subject to three dilemmas: internal, practical and ethical. From this, it can be concluded that while some reversibility is both desirable and feasible, ‘full’ technological reversibility would be neither. It also means that while developing and implementing nuclear energy technologies, one cannot simply tick the proverbial ‘reversibility’ box and be done with it. Rather, for those committed to reversibility, it presents an obligation that is both technology- and context-specific and requires infinite negotiation.

6.5. Main Research Question: What are the implications of reversibility for the responsible development and implementation of nuclear energy technologies?

This section provides an outline of the most important implications of these results for developing and implementing nuclear energy technologies in a responsible way.

First, the *extent* of the implications of reversibility ultimately depends on whether nuclear energy technologies should be reversible at all, because if so, this would give us reason to incorporate reversibility considerations into their development and implementation. Chapter 3 gave us reason to do so[167] if that development and implementation is to be done responsibly[168]. However, as the *ethical* dilemma that also follows from chapter 3 implies, the need for reversibility would still have to be weighed against other morally relevant factors, such as potential benefits, safety, security, possibilities for learning, etc.

On top of this, the Levinasian framework in chapter 3 has a number of general implications for how the responsible development and implementation of (nuclear energy) technologies is to be organized. That is, it calls for a subordination of technology development to a *just politics* that is open to the Other, allowing vulnerable others to influence the innovation of both politics and technology. For nuclear energy technologies, this might be particularly difficult to achieve (see section 6.2).

Consistent with this subordination of technology development to a just politics, this thesis has also demonstrated the importance of the 'socio-political' aspects of technology development and implementation for technological reversibility, Whether in terms of symbolic and institutional elements/micro-irreversibilities in chapters 2 and 5, politics in chapter 3, or the social/plan hierarchies and social stock of knowledge in chapter 4, the way in which nuclear energy technologies are societally embedded was shown to have a profound impact on their reversibility, or more specifically, on the ability to fulfil the first condition of technological reversibility.

Despite the fact that some of the implications of the *first condition* for reversibility refer to the development of technologies (e.g., in emphasizing the availability and viability of technological alternatives), the majority of strategies that were identified to help fulfill this condition (see section 6.3.1)[169] do not

[167] To be sure, even if chapter 3 were insufficiently convincing to show the general desirability of technological reversibility, it would still be *prima facie* desirable based on the social experimentation framework (see section 1.1).

[168] In saying this, I am not aiming at the 'foundational' relation between responsibility and innovation, since that is metaphysically given. This is about the '*ethical*' relation between the two terms, which would hopefully also lead to better 'structural' outcomes of innovation.

[169] Most of these strategies for making nuclear energy technologies more reversible would also be compatible with a Levinasian techno-politics.

primarily refer to the characteristics of nuclear energy technologies themselves. Instead, they refer to the discourse(s) and institutions that accompany them, both before and after their initial implementation. As such, the first condition for technological reversibility has major implications for how to *organize* both *the development and the implementation* of nuclear energy technologies.

While fulfilling the first condition for reversible nuclear energy technologies mainly has implications for how we discursively and institutionally embed such technologies, the implications of the *second condition* centers on the way these technologies are designed. That is, the strategies identified in this dissertation for fulfilling the second condition indicate that maximizing the ability to undo the undesirable consequences of a nuclear energy technology involves designing that technology according to certain design strategies rather than others (i.e., remediation or reconstruction over containment and compensation). For example, designing geological repositories so as to ensure long-term retrievability of SNF and HLW would give a more prominent role to the 'reconstruction' strategy over 'containment', allowing for retrieval in case the repository fails or P&T becomes viable (see sections 5.2 and 5.4)[170]. In sum, the second condition for reversibility mainly has implications for *the development stage,* with a *focus on the design* of nuclear energy technologies.

On top of all this, the *internal* dilemma of reversibility (also called the reversibility paradox in section 6.4) implies that the concrete implications of reversibility for the responsible development and implementation of nuclear energy technologies are not only limited by having to weigh reversibility against other relevant considerations, but also by the fact that strategies to fulfill the conditions may be incompatible with one another. That is, strategies that would help to fulfill one of the conditions might impair the ability to fulfill the other, thus limiting the extent to which reversibility can be realized. With its discussion of P&T, chapter 5 provided at least one example of such an internally dilemmatic situation. That is, P&T might be preferable to GD in terms of undoing undesirable consequences, but it runs the risk of becoming at least as locked-in. Of course, whether other nuclear energy technologies will suffer similar difficulties and which condition should be given priority, however, depends on the specific context, consequences and technologies involved.

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170 In light of the ethical and practical dilemmas, the desirability of such a design change towards more reversibility ultimately depends on how it weighs up against other relevant considerations, such as safety or the ability of the repository to actually work properly.

In all, the context-dependence, technology-specificity and dilemmatic aspects of reversibility considerations prohibit a one-size-fits-all or algorithmic solution to the question of what reversibility's concrete implications are. Still, the results suggest that reversibility considerations would require significant changes to the way these technologies are designed, the institutions through which we develop and implement them, the relation between those developing and implementing the technology and those that are not, and our readiness to accept when a nuclear energy technology should be reversed (or partially reversed)[171]. Even though these changes may be particularly challenging for nuclear energy technologies, I hope that the results of this dissertation can serve as guidelines for developing more concrete proposals towards the reversibility of nuclear energy technologies.

6.6. Further Generalizations and Limitations

All of the above has been focused on reversibility in one technological domain: nuclear energy technologies. Within that domain, it has specifically focused on technologies for energy production, fuel processing and radioactive waste management (and not, for example, uranium mining). In spite of this focus, some of the insights from this research are generalizable to other technological domains in which there is significant uncertainty about future risks, such as nanotechnology, biotechnology or ICT (Pieters, Hadziosmanovic, & Dechesne, 2014; Robaey, 2016b; Spruit, 2017). If innovators wish to experiment responsibly with such innovations in society, they should also be prepared for learning that the experiment is no longer responsible or desirable (e.g., Jacobs et al., 2010; Robaey, 2016a; van de Poel, 2016). In other words, experimenting responsibly with these new technologies also requires some degree of reversibility. The Levinasian reflection on technology in this dissertation corroborates this general need for technological reversibility. That is, the dilemmatic structure of techno-politics (inherited from the Levinasian conception of justice) prescribes that all technology and politics be open to change. However, the concrete applicability of this particular take on the issue is inevitably limited. That is, the 'transcendental'

[171] In section 6.4, it was said that 'full' reversibility was not feasible. However, this is not the meaning of 'reversed' that is aimed for here. Rather, 'reversed' refers here to the two conditions for reversibility being fulfilled, whereas 'partially reversed' refers to only the second one being fulfilled (see section 6.1).

approach to philosophy of technology that the Levinasian analysis represents tends not to provide the practical insights necessary to navigate the ethical dilemmas that it identifies (Verbeek, 2005). For example, it provides little guidance on how to balance a technology's reversibility with its concrete (ethical) efficacy, and it does not discriminate between different technologies and how they necessitate more or less reversibility considerations.

As such, this thesis leaves a number of concrete and ethically relevant questions unanswered that ideally would be the subject of future research. For one, it is still unclear how reversible a technology should be, practically speaking. That is, while it is clearly morally desirable to increase reversibility as long as it does not interfere with the fulfillment of other values, it is unclear how much weight reversibility carries in necessary value trade-offs. Such trade-offs would require additional ethical reflection (cf. Manders-Huits, 2011). Also, while the conditions for technological reversibility are sufficiently general to be applicable to other technological domains, it is still unclear to what extent they should each be fulfilled separately and how they are to be balanced in case they are at odds with one another. On top of all this, the conditions for technological reversibility do not prescribe *who* should fulfill them. For GD, it was proposed that an 'authorized body' should fulfil the first condition, whereas the second condition was discussed in terms of design strategies. However, while this may be applicable to technologies like GD that are subject to centralized management and control, it is doubtful whether it is equally applicable to technologies that lack such a centralized governance structure, such as nanoparticles (Spruit, Hoople, & Rolfe, 2016) or genetically modified seeds (Robaey, 2014). Moreover, while the ability of an 'authorized body' to fulfil the conditions is sufficient for reversibility *in principle*, this focus on central authority ignores other aspects that contribute to reversibility, such as the opportunities for policy outsiders to influence the continuation of experiments with technology in society (see chapter 2). As such, while the 'anonymity' of the conditions for technological reversibility means that they are generalizable to other technological domains, they require case-specific and theory-appropriate operationalization before they can become useful in assessing and guiding experiments with these technologies (as this dissertation partially did for GD).

Lastly, some of the insights developed for answering the third subquestion can also be applied to technology more generally. For example, the conceptualization of technology development as a process of structuration of human aspirations or the phenomenological perspectives on path dependence developed in this thesis are largely neutral with respect to the technology discussed. However, a number of limitations still apply. For one, this dissertation focuses on explanations for technological irreversibility based on positive feedback. As such, they are more focused on how irreversibility arises (which is relevant in *avoiding* irreversibility) than on how it is maintained. Also, it must be reiterated that there are theories of technological or institutional irreversibility that do not rely primarily on positive feedback to adoption, such as those based on sunk costs or structural inertia (Sydow et al., 2009). For some technologies, these theories may be more appropriate for understanding their irreversibility and would thus lead to different recommendations on how to avoid it. Secondly, the focus on nuclear energy technologies in this thesis invited theory development with an emphasis on symbolism and power. However, this may also have led to an insufficient appreciation of the economics of nuclear energy technologies in explaining their irreversibility (Collingridge, 1983; Cowan, 1990). As such, it may have missed opportunities for formulating strategies to avoid lock-in based on nuclear energy's economic specificities (e.g. long lead times, large investment costs, etc.). A third point concerning the recommendations on how to avoid irreversibility focusses on the design strategies for undoing undesirable consequences, i.e., remediation, reconstruction, containment and compensation. These are limited to material consequences of nuclear energy development and deployment, more specifically the risks connected to HLW. However, given that technology development (as conceptualized in this work) results in institutional and symbolic elements next to the material ones, additional strategies would need to be developed on how to make it possible to 'undo' those.

7 Implications of Reversibility for Responsible Experimentation

As established in chapter 3, nuclear energy technologies should be reversible to an extent. Without further analysis and reflection, however, this dissertation cannot conclude much more regarding the general desirability of such technologies in and of themselves. Nevertheless, it does provide relevant insights on the implications of reversibility for responsibly *experimenting with nuclear energy technologies in society*. These implications can be divided into two broad categories: one concerning the implications of this dissertation's conceptualization of reversibility and how to achieve it, and the other about the desirability of the reversibility of nuclear energy technologies and its relation to the other conditions for responsible experimentation. Both are briefly discussed below.

7.1. Implications of the two conditions for technological reversibility

In answering the first and third subquestions, this thesis presented a novel notion of technological reversibility in terms of two conditions, and a number of strategies for fulfilling them. The first condition for technological reversibility is concerned with the ability to stop the further development and deployment of a nuclear energy technology in society. Fulfilling this condition requires practical strategies aimed at keeping other technological options available and viable, avoiding asymmetrical resource distributions in favour of those who support the dominant technology, keeping value commitments flexible, and ensuring possibilities for criticism and novel discourse about it. The second condition involves the ability to undo the undesirable outcomes of the development and deployment of the nuclear energy technology in question. For material outcomes at least, fulfilling this condition involves designing nuclear energy technologies according to the preferable strategies for undoing their undesirable consequences (i.e., remediation and reconstruction rather than containment and compensation). For HLW and SNF management at least, this could affect the way we design and implement GD by allowing for long-term retrievability, but could likewise affect the entire fuel cycle by demanding P&T.

At least some of these conditions for technological reversibility and the strategies for fulfilling them should be included in the more general list of conditions for responsible experimentation. They could either directly serve as new conditions for responsible experimentation with nuclear energy technologies (insofar as they are not already integrated into the list in table 1.1) or they could simply provide inspiration for the formulation of other new conditions. For example, the strategy of 'keeping other technological option available and viable' might inspire the following condition for responsible experimentation: "There must be at least one technological alternative available that could replace the experimental technology". However, it is not entirely clear which are the best candidates for being turned into conditions for responsible experimentation: the two more general conditions for technological reversibility or the more practically-oriented strategies for fulfilling them. The current list of conditions for responsible experimentation in table 1.1 (van de Poel, 2016) offers conditions at different levels of abstraction, some resembling the conditions for reversibility, others resembling strategies for action. For example, condition 6 (flexible set-up of the experiment and avoidance of lock-in of the technology) could easily be construed as a strategy for achieving condition 3 (possibility and willingness to adapt or stop the experiment).

Nevertheless, this difficulty has an interesting implication for the general framework of responsible experimentation with new technologies in society. That is, the distinction employed in this thesis between a) conditions for reversibility in terms of capabilities and b) more technology- and context-specific strategies for fulfilling these conditions may actually provide a useful template for an extension of the framework for responsible experimentation with new technologies in society. The current framework links its conditions to relevant values, which allows for their mutual revision based on reflection and experience (van de Poel, 2016)[172]. Explicitly adding a level of practical strategies that operationalize the conditions allows for a more structured inclusion of these considerations in the mutual revision of the values, conditions and the way in which those conditions are to be fulfilled. This could potentially increase context-

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[172] Such a dynamic of normative learning and justification is similar to the one found in Wide Reflective Equilibrium (WRE), an approach to ethical reflection and justification that seeks coherence between ethical background theories, moral principles and considered judgements through their mutual revision (Daniels, 1979, 1996). This dynamic was already a model for normative learning in the responsible experimentation framework (van de Poel, 2016 p. 683).

sensitivity of the framework and facilitate normative learning (Taebi, 2016), help to improve and justify the case-specific operationalization of the conditions (Doorn & Taebi, 2017), and support the inclusion of stakeholder into the moral debate on real-life experiments with new technologies (Barilan & Brusa, 2011; Cotton, 2009; Doorn, 2010; Doorn & Taebi, 2017; van de Poel & Zwart, 2010). Of course, all of this could also facilitate responsible experiments with nuclear energy technologies in society.

7.2. Implications of the desirability of reversibility

In addition to formulating the conditions for technological reversibility and the strategies to fulfil them, this dissertation provided support for the position that it is desirable for nuclear energy technologies to exhibit a degree of reversibility. On the other hand, it also established that these technologies cannot be completely reversible. Based on this, one could conclude that responsible experimentation with nuclear energy technologies in society is impossible, since a reversibility *condition* for responsible experimentation with nuclear technologies can never be completely fulfilled. By extension, since the unattainability of complete reversibility is not limited to nuclear energy technologies, this line of reasoning would prohibit *any* responsible experiment with new technologies in society. Clearly, this is an unsatisfactory conclusion. Nevertheless, it does point to the fact that reversibility conditions for responsible experimentation require qualification. The practical and ethical dilemmas inherent to technological reversibility (see section 6.4) already implied as much by showing that reversibility necessitates trade-offs between (ethical) efficacy and reversibility. Likewise, trade-offs between reversibility and other values are possible, e.g., between reversibility and short-term safety in considering retrievability considerations in GD. Reversibility conditions are, however, not unique in being impossible to completely fulfill or involving trade-offs. For example, condition 4 in table 1.1 (containment of risks as far as reasonably possible) is qualified by a reasonability constraint based on the ALARA principle[173] (as low as reasonably achievable)(e.g., ICRP, 1977, 2007) because risks cannot be completely elimi-

[173] The ALARA principle has a rich history in radiological protection, where it provides important ethical and precautionary constraints to radiation exposure (e.g., Eggermont & Feltz, 2008). However, its application extends beyond nuclear energy-related activities and into other fields such as radiation protection in healthcare and exposure to environmental pollutants.

nated and even their partial containment comes at a cost. Along similar lines, I would propose that reversibility conditions be subject to an ARARA principle (as reversible as reasonably achievable), where the reasonableness is determined by the effect of more stringent reversibility measures on the expected benefits of the experiment, the nature and magnitude of possible hazards, and the possibility of fulfilling the other conditions for responsible experimentation with nuclear energy technologies. However, given that these hazards and benefits are not entirely understood when experimenting with new technologies in society, the utilitarian considerations that usually guide ALARA application (e.g., using cost-benefit analysis to weigh costs of reducing radiation exposure against other social and economic factors)(Hansson, 2013; Lierman & Veuchelen, 2005) are probably not a great fit for the context of experimentation . Moreover, the effects of increased reversibility on the possibility of fulfilling the other conditions for responsible experimentation does not lend itself well to a translation into clear 'costs and benefits'. As such, while the *need* for a qualifying reasonability constraint like the ARARA principle is implied by some of the outcomes of this dissertation (i.e., the dilemmas of reversibility and the need to weigh the need for reversibility against other relevant considerations), guidelines for actually performing it cannot be directly imported from current practice with ALARA and have to be relegated to future work.

Concerning the latter considerations, it must be noted that this thesis has not systematically investigated how exactly reversibility relates to the other conditions for responsible experimentation with new technologies in society. Nevertheless, a significant number of those conditions is clearly *compatible* with reversibility as understood in this thesis, while none straight-forwardly contradict it[174]. For example, the demand for experiments to be adaptable and stoppable, a flexible set-up of the experiment, and the reversibility of harm all contribute directly to fulfilling the two conditions for technological reversibility developed in this thesis. Along similar lines, 'consciously scaling up the experiment' can help to avoid path dependence and lock-in. The 'containment of risks' echoes one of the four strategies for the undoing of undesirable outcomes proposed in chapter 5. This indicates that the 'containment of risks' condition

174 However, most of these 'compatible' conditions for responsible experimentation lean towards one of the two conditions for technological reversibility. As such, the internal dilemma of reversibility indicates that fulfilling one of these 'compatible' conditions does not necessarily lead to an overall increase in reversibility.

should either fall under the 'reversibility of hazards' condition, or deserves to be reformulated in terms of risk avoidance rather than their containment. Lastly, the focus on democratically approved bodies, informing experimental subjects and providing opportunities for them to influence the experiment are compatible with avoiding resource asymmetries between agents as well as helping to avoid lock-in based on power explanations for path reinforcement. For the remaining conditions for responsible experimentation, such as better monitoring while addressing privacy concerns or the fair distribution of risks and hazards, however, it remains unclear how they relate to reversibility. Nevertheless, they should presumably provide limitations on how much reversibility is actually desirable or justifiable.

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About the Author

As of December 2017, Jan Peter Bergen is a post-doctoral researcher in philosophy of technology at the University of Twente. He completed his PhD in ethics of technology at Delft University of Technology between March 2012 and December 2017. Generally speaking, his work is influenced by philosophical pragmatism, 20th century phenomenology and social theory, STS, and technology dynamics. For more recent activities, however, he has also drawn inspiration from liberal philosophy of law, value-sensitive design theory, and the philosophy and sociology of death.

Besides his research, Jan has is an avid educator, having coordinated or assisted in a wide array of university level courses. Thematically, these ranged from strategic management and technology/impact assessment to the ethics and philosophy of science, engineering and design.

Jan has a multidisciplinary educational background. He holds a Bachelor's and Master's degree in Product Development from the University College of Antwerp. He also holds an MSc in Industrial Ecology from Leiden University.

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Samenvatting

De ontwikkeling van kernenergietechnologieën in de tweede helft van de 20^{e} eeuw bracht hoge verwachtingen met zich mee inzake het wederopbouwen van naties die getroffen waren door het geweld van de Tweede Wereldoorlog of die recent van de koloniale heerschappij waren bevrijd. In landen als Frankrijk, India, de USA, Canada, Rusland en het Verenigd Koninkrijk werd kernernergie het symbool van ontwikkeling naar een moderne en technologisch geavanceerde toekomst. Desalniettemin, na meer dan zes decennia ervaring met het opwekken van kernenergie, en in de nasleep van de kernramp in Fukushima, kan worden gesteld dat het opwekken van kernenergie niet zonder problemen verloopt.

Sommige van deze problemen vinden hun oorsprong in de feitelijke stoffelijkheid van de technologieën in kwestie. Zo brengen de hoogradioactieve materialen die worden gebruikt niet alleen risico's mee voor de huidige generatie (e.g., in de kans op een ramp bij kernsmelting van reactoren), maar in de vorm van hoog-radioactief afval van kernenergieproductie vormen ze ook een serieus intergenerationeel probleem waarvoor een acceptabele eindoplossing of de implementatie daarvan voorlopig ontbreekt. Daarenboven hebben kernenergietechnologieën ook bepaalde sociale en politieke gevolgen. Zo zijn ze bijvoorbeeld als autoritaire technologieën bestempeld (Winner, 1980) die centrale autoriteit, geheimhouding en technocratische besluitvorming vereisen.

Terwijl sommige van deze problemen konden worden voorzien vóórdat kernenergietechnologieën werden geïntroduceerd in de samenleving, staken andere problemen pas de kop op wanneer deze technologieën al verweven zaten in de sociale en technische structuur van ons leven. Daarbovenop worden er nog steeds nieuwe technologieën ontwikkeld (zoals reactoren van generatie III, III+ en IV), welke op hun beurt nieuwe en onzekere gevaren en risico's met zich meebrengen. Onwetendheid en onzekerheid over de mogelijke nadelige gevolgen van het introduceren van nieuwe technologieën zijn dan ook onvermijdelijk, zeker wanneer de technologie complex is, het over lange tijdsspannes gaat, of de risico's afhangen van sociale of politieke factoren die tijdens het ontwerpproces niet werden voorzien. Dat dient het ontwikkelen en implementeren van nieuwe technologieën echter niet in de weg te staan. Het zou ons eerder moeten motiveren om dit soort 'experimenten' met nieuwe technologieën in de samenleving (van de Poel, 2011, 2015) zo te organiseren dat

we zo effectief en verantwoord mogelijk kunnen *leren* over de mogelijke gevaren en risico's. Zo wordt het mogelijk om risico's te minimaliseren en om ongewenste morele, sociale of politieke ontwikkelingen te vermijden. Het verantwoord organiseren van zulke experimenten houdt evenwel in dat we op een bepaald moment mogelijk moeten concluderen dat het experiment niet meer verantwoord of wenselijk is. Moeten we op dat scenario voorbereid zijn, en zo ja, hoe doen we dat dan? Eén mogelijke strategie om hiermee om te gaan is het *omkeerbaar* maken van de technologie en haar introductie in de samenleving. Deze dissertatie stelt zich dan ook als doel om deze strategie verder te verkennen door een antwoord te bieden op de volgende onderzoeksvraag (RQ) en bijhorende deelvragen (SQ):

RQ: *Wat zijn de implicaties van omkeerbaarheid voor het verantwoord ontwikkelen en implementeren van kernenergietechnologieën?*

SQ1: *Onder welke voorwaarden kunnen kernenergietechnologieën als omkeerbaar worden beschouwd?*
SQ2: *Waarom zouden kernenergietechnologieën omkeerbaar moeten zijn?*
SQ3: *Zo ja, hoe kan de omkeerbaarheid van kernenergietechnologieën worden bereikt?*

Na het inleidende hoofdstuk 1 leveren de hoofdstukken die het hart van deze dissertatie vormen allen een een specifieke bijdrage aan het beantwoorden van de drie deelvragen en zodoende ook aan het beantwoorden van de hoofdvraag. Onderbouwd door drie historische casestudy's over de ontwikkeling van kernenergietechnologie (i.e., India, Frankrijk en de USA) beantwoordt hoofdstuk 2 de eerste onderzoeksvraag door het formuleren van *de twee voorwaarden waar kernenergietechnologieën aan moeten voldoen om als omkeerbaar beschouwd te worden*, i.e., 1) het moet mogelijk zijn om de verdere ontwikkeling en implementatie van de technologie in de samenleving stop te zetten, en 2) het moet mogelijk zijn om de ongewenste gevolgen (materieel, institutioneel of symbolisch) van de ontwikkeling en implementatie van de technologie ongedaan te maken. Hierna behandelt hoofdstuk 3 de tweede onderzoeksvraag door *de algemene wenselijkheid van technologische omkeerbaarheid* aan te tonen op basis van de relatie tussen technologische omkeerbaarheid en verantwoordelijkheid in de ethische fenomenologie van Emmanuel Levinas. Hoofdstuk 3 stelt namelijk dat technologieontwikkeling een antwoord is op onze verantwoordelijkheid dat die verantwoordelijkheid echter steeds tekortdoet, wat onophoudelijk de vraag naar technologische en politieke verandering oproept. Nadat zo beargumenteerd is dat kernenergietechnologieën idealiter omkeerbaar zouden moeten zijn, ontwikkelen hoofdstukken 4 en 5 specifieke strategieën om technologische omkeerbaarheid te bereiken. Om te beginnen onderzoekt hoofdstuk 4 *de processen die het moeilijk maken om de verdere verdere ontwikkeling en implementatie van een kernenergietechnologie in de samenleving stop te zetten*, en levert zo input voor het vervullen van de eerste voorwaarde voor de omkeerbaarheid van kernenergietechnologieën. Het doet dit door een fenomenologisch perspectief op technologie en haar adoptie te ontwikkelen, gebaseerd op het werk van Alfred Schutz. Daarnaast verkent het ook verschillende manieren waarop de padafhankelijke processen die leiden tot technologische lock-in door technologieadoptie worden aangestuwd. Hoofdstuk 5 onderzoekt de geschiedenis van geologische berging van hoogradioactief afval in de USA. Het identificeert daarbij een aantal concrete valkuilen voor beleidsvorming die kunnen leiden tot lock-in en dus moeten worden vermeden. Het presenteert ook een aantal algemene *ontwerpstrategieën die het ongedaan maken van de ongewenste gevolgen van een technologie kunnen faciliteren*, en draagt zo bij aan het vervullen van de tweede voorwaarde voor de omkeerbaarheid van kernenergietechnologieën.

Hoofdstuk 6 vat de belangrijkste bevindingen van de dissertatie samen en geeft aan hoe deze bijdragen aan het beantwoorden van de onderzoeksvragen. Daarbij reflecteert het ook op een aantal complicaties die de kop opsteken bij omkeerbaarheidsoverwegingen. Op basis hiervan kan worden gesteld dat de kwestie van onomkeerbaarheid en omkeerbaarheid context- en technologiespecifiek is, en geen binair gegeven maar eerder één van gradatie. Het hoofdstuk sluit af met algemenere implicaties en beperkingen van de onderzoeksresultaten. Als laatste reflecteert hoofdstuk 7 op de implicaties van de resultaten van deze dissertatie voor verantwoord experimenteren met kernenergietechnologieën in de samenleving.

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Simon Stevin (1548-1620)

'Wonder en is gheen Wonder'

This series in the philosophy and ethics of technology is named after the Dutch / Flemish natural philosopher, scientist and engineer Simon Stevin. He was an extraordinary versatile person. He published, among other things, on arithmetic, accounting, geometry, mechanics, hydrostatics, astronomy, theory of measurement, civil engineering, the theory of music, and civil citizenship. He wrote the very first treatise on logic in Dutch, which he considered to be a superior language for scientific purposes. The relation between theory and practice is a main topic in his work. In addition to his theoretical publications, he held a large number of patents, and was actively involved as an engineer in the building of windmills, harbours, and fortifications for the Dutch prince Maurits. He is famous for having constructed large sailing carriages.

Little is known about his personal life. He was probably born in 1548 in Bruges (Flanders) and went to Leiden in 1581, where he took up his studies at the university two years later. His work was published between 1581 and 1617. He was an early defender of the Copernican worldview, which did not make him popular in religious circles. He died in 1620, but the exact date and the place of his burial are unknown. Philosophically he was a pragmatic rationalist for whom every phenomenon, however mysterious, ultimately had a scientific explanation. Hence his dictum 'Wonder is no Wonder', which he used on the cover of several of his own books.