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Shocks, institutional change, and sustainability transitions

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The role of exogenous shocks in influencing transition processes is of significant interest to a wide variety of research in sustainability science (SS). Such events disturb and interrupt path-dependent processes in sociotechnical systems. Sometimes this can lead to radical departures from existing trajectories, while at other times existing systems can be more resilient, adapting, or reconfiguring in response to a shock. In this paper, we explore the role that exogenous shocks can have on institutional change. The sustainability transition literature, as shaped by the multilevel perspective, has usually focused on shocks as windows of opportunity (WoO) where alternatives can break through due to strategic action. We offer the perspective of imprinting, which places primary attention on shocks leading to immediate and irreversible institutional change with long-term consequences. The usefulness of this concept is explored by examining the impact of two major shocks to the energy system: World War II and the 1973 oil crisis. It is concluded that the imprinting concept enables analysis that is attentive to how the underlying institutions of a system can be rapidly and deeply altered by the dynamics of exogenous shocks. It is argued that imprinting is an important complementary concept, next to windows of opportunity, for sustainability science research aiming to understand the period of turbulence we are living through.

Significance

Shocks such as wars, financial crises, and environmental disasters, play an important role in influencing the direction of sociotechnical systems such as energy, food, and mobility. We develop understandings of the effects of shocks on systems through the concept of imprinting, which looks at how the different conditions of a time-restricted period of a shock can bring about rapid changes in sociotechnical systems with long-lasting changes. We explore this concept through analysing two shocks and effects on the energy system: World War II and the 1973 Oil crisis. Prospective sustainability transitions will be effected by shocks such as climate change impacts and conflicts and thus understanding the long-term effects of shocks through imprinting will be a useful additional perspective.

1. Introduction: Sustainability in a Time of Perpetual Crisis

We live in an age of perpetual crisis. These were the words of British journalist Andy Beckett in a Long Read piece for the *Guardian*. The date of that article is remarkable in hindsight: 17th December 2019 (1). One did not have to wait long to see a once-in-a-lifetime global pandemic that uprooted every facet of society, and a subsequent war in the heart of Europe: the invasion of Ukraine by Russia, contributing to an energy crisis. These are stark examples of what are labeled *exogenous shocks*, recognized in Sustainability Science (SS) as important for understanding sustainable development. Shocks cover phenomena including natural disasters, industrial disasters, environmental tipping points, climate change-related disasters, depressions, and sudden and steep break-ups of supply chains, as well as wars and revolutions (2). How do shocks influence institutional change in sociotechnical transitions?

To answer this question, we mobilize the multilevel perspective (MLP). Here, exogenous shocks are disruptions in the timelines of path-dependent evolution in sociotechnical systems. These systems consist of: 1) a set of aligned elements or components that together provide for basic needs such as energy. There is not an established list of components, and often this dimension is focused on technology. However, in the literature, there is reference to other components which ensure that technologies are stable and perform, such as industrial strategies and business models, policies and regulations, user preferences, and cultural symbols; 2) actors whose actions maintain or improve the system; and 3) rules actors use to guide their behavior (3, 4). The total rule-set is often referred to as a regime, and, following North and Giddens and more broadly institutional theory, rules should be interpreted as institutions that constrain or enable specific actor behavior (5, 6). Actors who use these rules are called regime actors. This rules-based definition of institutions is aligned with general social science institutional analysis of shocks.

Following Geels et al. (in this issue), we treat these systems as similar to production–consumption systems as analyzed in the SS literature and take the MLP as a starting point. This framework or heuristic focuses on sustainability transitions occurring as a result of interactions between niches, regimes (rule-sets) expressed in sociotechnical systems, and landscape developments, including shocks and trends. Stability is located at the level of the regime through the formation of rules, both informal and formal. Rules guide and shape action and create path dependencies that lead to inertia, making regimes and thus systems difficult to change. Niches are incubators of new systems and regimes and struggle to spread more widely because of path dependence at the regime and system levels.

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We seek answers to our research question by exploring how shocks (operating at the landscape level) influence changes in rules in the energy system. We analyze two case studies to assess how the energy system has been affected by shocks: World War II (WWII) and the 1973 oil crisis. Shocks deserve particular attention because in the coming decades shocks are expected to happen more often due to the climate and biodiversity crisis, growing inequalities, and the implicated growing potential for conflict and war (7). While these shocks will have major and horrible consequences, they may present opportunities for more rapid system change toward sustainability through interrupting established path dependencies within regimes (8). The role of shocks is therefore of notable interest to diverse strands of SS research, including (for example) environmental economics (9), socioecological systems and resilience (10), and environmental governance (8).

Rather than discuss differences between these diverse contributions to the SS literature, more important is to illustrate commonalities: a given focal entity—be it a system, a sector, or a policy regime—develops in incremental and path-dependent ways, where particular processes become routine and over time gather momentum, making such a focal entity difficult to change. Across such research, a shock is something that is external to the dynamics of the focal entity and can lead to pressure being exerted on the focal entity in question. These diverse perspectives recognize shocks and uncertainty as a source of branching points where alternative trajectories become possible (2).

Exogenous shocks have been analyzed in a variety of ways, including "punctuated equilibrium theory" (11), the "critical junctures" approach (12), and the multiple streams approach (13). In MLP research, the dominant way in which shocks have been understood is as windows of opportunity (WoO), where a shock places pressure on the sociotechnical regime and actors can influence a change in direction toward sociotechnical niches (14). Shocks are thus moments in which different options may become available to policymakers that were previously hard to consider due to path dependencies (13). However, as Geels et al. (15) point out in their analysis of COVID-19 recovery policies, there is often an overly optimistic narrative concerning shocks and the ability for change toward more sustainable alternatives to take place. There is also a need to focus on constraining contexts. Geels et al. refer to "critical antecedents" or conditions that existed prior to a shock, such as the national institutional context, which constrain the options for strategic actions.

We follow this call for a focus on constraining factors in addition to enabling factors in relation to the study of shocks, but in a different way. In this paper, we primarily focus on the constraints of the sudden new conditions put in place by the shock itself, rather than the critical antecedents or conditions that existed prior to the shock (16, 17). Here, we follow imprinting theory, in which a shock may not just provide a window of opportunity but may in fact generate an immediate, irreversible change. Widely used for multilevel analysis in organizational studies (18), imprinting theory places primary attention on the dynamics of the time-restricted period of a shock and the effects of these dynamics, rather than on how different actors respond and attempt to enact change. This theory lends itself well to original encapsulations of shocks by Rip and Kemp as part of a sociotechnical landscape, understood as an environment in which sociotechnical change takes place (19). For example, they describe WWII as a fundamentally different selection environment for innovation to that which existed before the war.

In section 2, we contrast imprinting perspectives with the prevailing perspective of windows of opportunity (WoO). In section 3, we discuss our explorative case study methodology, examining the impact of two major shocks to the energy system: WWII and the 1973 oil crisis. Our analysis is presented in section 4, followed by a discussion in section 5, in which we evaluate the usefulness of the imprinting perspective for sustainability science, and in particular for a world that has seemed increasingly shocking in recent years.

2. Exogenous Shocks and the MLP: Contrasting Windows of Opportunity (WoO) and Imprinting

In this section, we elaborate on the imprinting concept by contrasting it with the WoO perspective, outlining why it offers new insights for MLP analysis of shocks. The notion of WoO as moments in which niches can break through forms a core part of the overall MLP heuristic. This is evident from the core MLP diagram itself, where it is stated: "landscape developments put pressure on [an] existing system, which opens up, creating windows of opportunity for niche-innovations" (20, p. 11). WoO are moments of enhanced agency in which niche actors who struggle to have their solutions adopted during the normal path-dependent development of sociotechnical systems can gain a foothold due to pressures on regime actors, who may not have an immediate adequate response. This, however, takes political work and involves struggles by political coalitions or the construction of particular narratives around a shock in order to forward particular agendas (21). The degree to which an opportunity arises can be influenced by the institutional context of a particular country that existed prior to a shock (15), but, nevertheless, a shock affords agency to particular agendas, such as the nuclear phase-out decision made by Germany after Fukushima (22). In MLP terms, the effects of a shock are influenced by the stage of maturity of sociotechnical niches and regimes (23).

The WoO concept is widely used in agenda-setting theory; it was developed by Kingdon in his seminal work exploring how particular issues become prevalent at certain times and how policy can change based on the coupling between different streams of activity, including the problem, policy, and politics streams (24). The primary focus is therefore on the evolutionary development of independent streams in the policy-making process, and how they become coupled. A window of opportunity is a moment in which coupling becomes attractive because solutions are coupled to problems by policy entrepreneurs (13). However, WoO may also become more likely due to a focusing event such as a war or natural disaster resonating with the MLP notion of a landscape shock (25).

In contrast, imprinting theory has a primary focus on the exceptional conditions of a particular time-restricted period, which leaves less room for choice (26). Understanding the biological and psychological roots of the imprinting concept helps in understanding this point (18). In biology, imprinting theory focuses on how a particular traumatic period in the development of a human or animal can be "stamped" onto their being, with long-term consequences. A famous example, outlined by biologist Konrad Lorenz, demonstrated how ducklings estranged from their mother during a sensitive period in early life will not recognize their mother once they are reunited after the period, instead acting as if what was present during the sensitive period—such as a scientist or even a prominent inanimate object—is their mother (27). In psychology, traumatic childhood events can form mental imprints of sensory and affective elements of the traumatic experience, which are causal factors for enduring traits in adult life (28). These time-restricted periods do not simply interrupt development as a shock, and provide a new context for making choices. On the contrary, the event is directly constitutive of subsequent pathways.

In organizational studies, imprinting research was taken forward by Stinchcombe in his study of how organizations founded during particular time periods were influenced by and continued to reflect the wider social relations of those periods (29). The theory was developed to understand the processes through which an organization can come to reflect the conditions of a particular time-restricted period even when that period has ended. A variety of topics have been analyzed using this concept (17). These include how organizations during the break-up of the Soviet Union continued to reflect enduring traits from that era in terms of organizational norms and practices despite changed economic and societal contexts (30), or how organizations continue to reflect the characteristics of a particular technological paradigm even when the paradigm in question is no longer dominant (31). Imprinting has been used in MLP research by Johnstone and McLeish, who explored how a time-restricted shock period (such as a war) exhibits different conditions to normal path-dependent times, and the effects these exceptional conditions have for sociotechnical developments in energy, food, and mobility (16, 32).

Imprinting takes a different perspective to WoO theory in relation to the role of agency and actors. WoO theory highlights how, through couplings between different streams (that may or may not include an external focusing event), a moment is reached in which a choice becomes possible between different pathways, and where policy entrepreneurs act as facilitators of choice (33). Regime actors may work toward preventing change; however, these moments also open up the potential for radical change through the work of advocacy coalitions pushing for alternatives and promoting niches (34). Imprinting theory is different, as the focus is rather on how new environmental conditions present a constraining and often traumatic factor that becomes stamped onto the focal entity, in this case, a sociotechnical system. To understand this stamping process, it is important to recognize the different perspectives offered by WoO and imprinting theories with regard to institutional change.

In WoO theory, what changes during a shock is the opportunity niches have to develop, a process that may be supported by regime actors. However, rules that existed prior to the shock—the genotype of a system—do not tend to change but instead act as critical antecedents constraining systemic change (15). In imprinting theory, the stamping process of the new environment can lead to a rapid change in underlying rules in a short space of time. As Dokko et al. point out, during the sensitive period, "cognitive models… can be challenged and replaced with scripts and schema that are more congruent with the new environment" (35, p. 55).

These different perspectives on agency and institutions are reflected in the different mechanisms focused on in each theory. Key mechanisms for change in WoO theory relate to policy entrepreneurs and actor coalitions promoting particular agendas at a time when there is a crack in the regime due to a shock. The mechanisms of imprinting in sociotechnical systems, on the other hand, focus on the dynamics of shocks as directly changing underlying rules, as a result of a number of mechanisms introduced by Johnstone and McLeish (16).

The first mechanism is demand pressure. A shock can lead to radically new conditions which present challenges for sociotechnical systems, such as the sudden cessation of supply of a particular energy fuel, or a radically increased demand for a particular energy source. Shocks can be distinguished based on how demand pressures differ between different shocks. The second mechanism is directionality, where a shock may foreground an existing directionality or create a new one. Here, a system can become directed by new visions and expectations that were not dominant prior to the time-restricted period. For example, during COVID, energy systems suddenly became geared around managing vastly reduced demand. The third mechanism is new policy capacities. Here, there is a new preparedness to act and new forms of collaboration between actors in response to an emergency situation, which differs from the negotiation of competing perspectives that is the focus of WoO perspectives. This process often involves the creation of new organizations in direct response to the new conditions of the shock period. An example here is the establishment in March 2022 of a new European Union-United States of America taskforce based on the aim of weaning the West off supplies of Russian gas, a result of the Russian war against Ukraine. The fourth mechanism is cooperation and shared sacrifice. In times of crisis, the general population may experience a shared condition where there is responsibility on everyone to "do their bit" in response to a crisis. This was evident in relation to COVID lockdowns and the need to 'stay at home to save lives' in the United Kingdom or rationing during the war.

The different contextual conditions presented by a shock can become stamped onto the sociotechnical system through systems reflecting the new environment of the shock period via a change in rules caused by the four mechanisms. While there is not the space to discuss this aspect of imprinting theory in detail, we note that imprinting theory also casts light upon the traumatic aspect of landscape shocks, and subsequent action can continue to be guided by experiences of a shock and efforts to avoid such situations again (32). War, for example, is often discussed in such terms; in Europe, historians note how a shared sense of "fear and freedom" at the end of WWII continued to shape developments in the post-war world. A powerful collective experience during a shock can have long-term consequences that influence subsequent action (36). Whether imprinting endures in the long term after the shock period has ended is explored through examining whether the changes in rules observed during a shock period persist or decay (16).

Taken together, imprinting offers the potential to analyze shocks as focal points of study that actively shape trajectories rather than simply interrupting evolving ones. Imprinting theory implies that during a sensitive period, one that exhibits different environmental conditions, rules can change. We explore this theory through assessing the extent to which the two shocks of WWII and the 1973 oil crisis, along with developments in the transatlantic energy system, fit with an account of imprinting (Table 1).

3. Framework and Methodological Approach

We focus on two contrasting case studies in relation to landscape shocks: World War II and the oil crisis of 1973. This approach involves examining diverse cases (37) because these two cases represent two important shocks to the energy system, while their long-term outcomes are recognized as being very different. The shock of WWII led to enduring change, while the oil crisis did not (38, 39). We will explore whether we can explain this difference using imprinting theory. Based on conclusions in the literature that a significant change in the energy system took place after the war that endured for decades but not after the 1973 oil crisis (40), our hypothesis is that imprinting should be absent from the 1973 oil crisis and present for WWII. We do not focus on comparing national developments; instead, we use the notion of a transatlantic zone. This is an area of deep transnational exchange and institutional connection that is affected in similar ways by shocks. A zone contains nation-states that share vulnerabilities, read each other's experiences, and share policy responses. The borders of a zone can be fuzzy, as connections and sharing experiences may not respect specific national borders. The result

Table 1. Overview of windows of opportunity and imprinting theories in relation to shocks

	Windows of opportunity	Imprinting
Disciplinary background	Rooted in agenda-setting theory; WoO come about due to the internal build-up of problems in a system in which external shocks may contribute to enabling decisions to be made toward alternative trajectories.	From organizational studies; aimed at understanding how a focal entity such as an organization or system comes to reflect exposure to particular environmental conditions during a sensitive period.
Definition of shock	Focusing event; a shock contributes to coupling problems and solutions, presenting an opportunity to promote particular niches.	A time-restricted period that exhibits particular environmental conditions, in which a focal entity is susceptible to influence from these conditions.
Agency	WoO enable greater agency, as there is more chance for particular niches to gain credibility during these moments through the work of policy entrepreneurs.	Imprinting shapes rules and agency in specific directions.
Institutions	Existing institutional arrangements can limit the degree of choice available; however, institutions do not change as a result of the focusing event.	Rapid institutional change can occur where new rules become stamped onto a socio-technical system due to the traumatic conditions of a shock.
Mechanisms of change	Dependent on the activities of different advocacy coalitions and policy entrepreneurs, a window may close with little change, or decisions taken may lead to the opening up of regimes for change via niche development.	Through new demand pressures, directionality, new policy capacities, and shared sacrifice specific to a particular shock, new rules become dominant.

of this spatial focus is that we try to identify commonalities, while occasionally paying attention to national specificities within the generic pattern (41).

To explore processes of imprinting, we focus on what developments occurred during the shock periods in terms of the four mechanisms of imprinting identified above: demand pressure, directionality, new policy capacities, and shared sacrifice, and how these shaped the rules of energy systems. We then explore whether these rules, influenced by the dynamics of the shock, persisted in subsequent developments or decayed. Our analysis relies on a wide variety of research from energy studies, political economy, and history in the construction of a plausible interpretive account. Our initial research focused on identifying literature focused on a long and broad interpretation of energy systems that encapsulated the transatlantic zone (38, 39, 42). We used a snowballing strategy to gather further relevant data that was useful for the interpretive task.

4. Analysis: The Role of Shocks in the Evolution of Transatlantic Energy Systems

4.1. WWII. The energy system faced significant new *demand pressures* as a result of WWII. WWII has been identified as "total war" by historians, meaning entire societies rather than dedicated militaries were mobilized toward achieving victory (43, 44). Sociotechnical systems became implicated in serving new demands brought about by wartime mobilization and navigating new barriers and constraints presented by conditions of warfare. This was a war in which access to oil was pivotal. As fighting got underway, conventional oil supply routes such as British Middle Eastern supplies were cut off through blockades. The United Kingdom and other allies became almost entirely dependent on oil produced in the United States, with 90% of British oil supplied from there (45). The US oil industry had to respond to the demand pressure of supplying this oil as well as the increased demand from greatly expanded fleets of aircraft. Meanwhile, a decisive factor in the war was that Germany did not have access to oil—this was an influencing factor behind certain invasions. The urgency of the war effort also impinged on the electricity system, where the crucial challenge was meeting increased industrial demand for wartime production. Cessation in supplies of oil or electricity would mean that crucial materials for military campaigns would not be produced in adequate time.

WWII as a total war created an overarching *directionality* or "singleness of purpose", which was to achieve victory. Under such conditions, the energy system was redirected toward prioritizing the needs of warfare. Maintaining supplies of oil was crucial for the war effort (46), and the war foregrounded advancements and deployments in oil infrastructure, including new wide-diameter pipeline construction in the United States, aviation pipelines in the United Kingdom, expansion of refinery capacity, and shipping fleets for oil transportation. Many innovations related to oil had no market prior to the war but were deployed solely for the purposes of war (47). In Germany, innovation was also stimulated by the demand pressure for oil. Due to not having access to an abundant supply of oil, Germany looked to produce synthetic petroleum from its coal supplies. Meanwhile, the electricity system became geared around interconnection and centralization of supply in order to ensure that increased demand for wartime production could be met. In addition to this, new, larger power plants were foregrounded as a solution to rising demand from factory production—through, for example, the construction of large hydroelectric power plant. Unexpected directionalities driven by wartime necessity would have important ramifications for the energy sector. For example, shortages of materials saw plastics increasingly utilized for storage and transportation of materials, further deepening dependence on oil production (48). Most famously, the rapid development of nuclear weapons at the time, although developed purely for military use, would have long-term consequences for the energy system.

The war saw enhanced *policy capacities* for decisive action regarding energy. The creation of new centralized government departments to manage sociotechnical systems and unprecedented scientific mobilization and organization resulting from the war is widely recognized in the literature (49–51). This can be seen in the widespread nationalization and suspension of competition in the energy system that took place in Europe (52, 53), but also in the United States and Canada. New wartime departments were

Table 2. Summary of rules in the transatlantic energy system during WWII

Rule	Summary
Imperative to use oil	Manifested in rapid transitions to oil in Europe and specific institutions designed to facilitate oil transition, such as the Marshall Plan.
Maintaining abundance and constant supply	Recognized new challenge of "orderly management of abundance"; transatlantic energy systems geared around rapidly expanding supply, rather than energy efficiency.
Centralization	This rule persisted in terms of policy and governance, with centralized institutions overseeing energy production as well as technology and infrastructure with centralized grids and increasingly large power plants.
Internationalization	During the war, Europe became a net energy importer predicated on the international supply of oil under the control of the United States. This trend continued after the war with increased cooperation between Europe and the United States and increased dependence on Middle Eastern oil

created to coordinate with industry for key resources such as petroleum and electricity supply (54, 55). Decisive action was taken on critical infrastructure through these new organizational structures. As well as these national policies, new international policy capacities were introduced to manage energy supplies through Allied committees on the coordination of supplies and materials for oil and fuel (56, 57).

Shared sacrifice is widely noted to have played a significant role during WWII (44) in preserving key energy resources such as oil. Rationing, for example, was brought in under the auspices of a shared sacrifice to ensure that victory could be achieved. Research has highlighted how this shared sacrifice instilled a powerful sense of duty, influencing households to cut back on their use of motorcars, for instance (36, 45). Shared sacrifice also enabled new forms of collaboration between formerly competing stakeholders. This is widely recognized in the historical literature as the virtual suspension of competition, alongside new forms of cooperation (44). Oil companies, for example, shared innovations to enable the construction of new pipelines, while grid operators had to collaborate across divergent grids to enable continual supplies of electricity. Greater awareness of the contribution made by different actors in society to a common effort during wartime is emphasized by historians (36, 44, 58); this had a powerful emotive effect on societies across the transatlantic zone (36).

4.2. Rules and the Persistence of Imprints after WWII. The exceptional conditions of war fundamentally reshaped the energy system. The mechanisms above were powerful mobilizing forces for significant change at the meso-level in terms of changed rules (outlined in Table 2). Trends experienced across belligerent nations included an imperative to use oil, centralization in terms of both policy making and technology (such as a preference for centralized electricity grids), internationalization through greater collaboration between national forces, and systems geared around maintaining abundance and constancy of supply because cessation of supply would mean losing the war. This widely contributed to the overproduction of oil and oil infrastructure in countries like the United States; this overproduction had to be reabsorbed into peacetime societies (40) (Table 2).

This new rule-set did not dissipate but constituted a new energy regime in the post-war world. WWII "laid the foundations" of a transatlantic system underpinned by abundant supplies of cheap oil (40). There is widespread agreement in the literature that a new and stable energy system developed in the aftermath of war across the transatlantic zone, leading to a number of trends (at the landscape level). There was rapid acceleration in the production and consumption of oil and petroleum. This was particularly the case in Western Europe, with the share of oil in primary energy consumption increasing from 10% after the war to 50% by the late 1960s, and increasing use of oil in a variety of sectors, including heating, agriculture, transportation, and electrification (59). There was a recognized trend toward centralized and integrated electricity production, based around economies of scale and a constant "baseload" production provided by increasingly large power stations constituting a stable paradigm of grid design (38, 60). Another trend was the abundant availability of energy at a low price as a new condition of the transatlantic energy system (61–63). There was also the development of stable national and international institutions for the delivery of energy production, many influenced by the wartime experience (63, 64).

The aftermath of war saw efforts to build peace via strategic decisions, including the Marshall Plan, which influenced rapid transitions to oil across Europe (65). However, what is noted in the literature is how these decisions were shaped in a new institutional context that had emerged due to the war itself (36). Thus, the institutions of WWII are referred to as being the "dress rehearsal" for the systems of the post-war world (66), and a new 'World War II regime' is identified as a new institutional context guiding sociotechnical developments (67). In MLP terms, we characterize this as a persistence of the rules that had been amplified in the energy system in the post-war period (16). Networks of oil supply had consolidated during the war, with the work of inter-Allied committees and American plans around Middle Eastern oil resources. Energy historians note how activities during the war had influenced the acceleration and stability of a paradigm of centralized electricity grids (55). Byrne and Rich (68) note how institutions associated with energy were inspired by wartime institutions, including weapons institutions, and that the new objective of energy policy was to ensure abundance, with efficiency being a secondary concern. Energy relations were defined by interdependence and cooperation across the transatlantic zone between the United States and Europe (69), and the new hegemonic position of the United States, which brought stability to the international oil regime, and was a position consolidated during the war (45).

We can thus see that the shock of war led to significant changes in rules on the meso-level, and that these new rules stabilized in the post-war world, suggestive of imprinting dynamics.

4.3. The 1973 Oil Crisis. In retaliation at the Israeli invasion of the Golan Heights in 1967, nations belonging to the Organisation of the Petroleum Exporting Countries (OPEC) launched an oil embargo against countries supporting Israel, including the United States, the Netherlands, and Portugal, and by 1974, the price of oil had quadrupled. A shared condition emerged of an urgent need to reduce oil demand and energy demand in general. This represented a new environment that sociotechnical systems were exposed to because

up to this point transatlantic energy systems had been guided by an assumed abundant availability of oil and increasing energy use (64). The oil crisis contributed immediately to "the common Western perception that the immediate threat was to energy security" (70, p. 6).

The overall change in *directionality* with regard to the energy system can be characterized as one that was guided by the urgent aim of reducing energy demand, particularly the demand for oil. This represented a decisively different direction to the condition of abundance; demand reduction had not been a predominant concern in the decades after WWII (40). Other changes in directionality were also motivated during this time-restricted period, such as the need to diversify supply. For example, France announced the Messmer Plan for the huge expansion of nuclear power as an alternative energy source, given that at the time most of France's electricity was dependent on foreign oil (71). The need to diversify energy supply and reduce import dependence became prime concerns which saw an increasing interest in research and development of renewable sources of power across the transatlantic zone (38).

New *policy capacities* emerged in response to the crisis, with the new condition of scarcity influencing decisive action. In the United States, emergency measures were brought in to curtail consumption of petrol, including rationing programs, gas stations being asked to close on Sundays, new speed limits, the implementation of daylight saving time, and homeowners being asked to refrain from putting up Christmas lights. In Europe, countries including the United Kingdom, Germany, Switzerland, Norway, and Denmark placed restrictions on driving and flying (70). In the United Kingdom, homeowners were advised to only heat one room in their house during winter. In addition, policies were developed in the United States enabling the state to directly control oil prices through the Emergency Petroleum Allocation Act 1973 (72). In Germany, among other countries, efficiency programs were introduced to target industrial users and make processes less energy intense. In addition to these national policies, there were efforts to coordinate a new international approach across the transatlantic zone in response to the actions of OPEC nations. This led to an international meeting of the US and European nations in February 1974, from which the International Energy Agency (IEA) would develop.

In this new emergency situation, the language of shared sacrifice was used and specifically drew on wartime language, particularly in the United States. President Richard Nixon, in the "Congressional Declaration of Purpose", emphasized that the struggle to reduce energy use was not just up to Washington but "lies in every home, in every community across the country. If each of us joins in this effort with the spirit and the determination that have always graced the American character, then half the battle will be already won" (73). The return of a form of energy rationing across the transatlantic zone could be seen to embody a spirit of shared sacrifice. However, authors note that there were considerable divergences of opinion, with many blaming their own governments and particularly oil companies for the crisis, rather than blame lying with OPEC countries (46, 74). Studies highlight that many citizens did not feel that the crisis was shared but rather that oil companies continuing to make significant profits were not taking on their fair share of the burden (46).

4.4. Rules and the Persistence of Imprints after the Oil Crisis. The 1973 oil crisis saw a rapid change in the rules of the transatlantic energy system. From a system geared around increasing abundance and the international supply of oil, new rules of reducing energy consumption, encouraging indigenous supply, and diversifying supply were discussed during this oil crisis (Table 3).

Table 3. Summary of rules in the transatlantic energy regime during the 1973 oil crisis

Rules	Trends during shock
Reduce energy consumption	Immediate imperative to reduce use of oil and electricity; policy interventions guided by this overarching aim.
Encourage indigenous supply	Search for solutions to supply shortages through utilizing indigenous resources.
Diversify energy supply	Find new ways of producing energy as an alternative to oil: coal, nuclear, renewables, and natural gas.

However, the imperative to reduce energy consumption appears to have dissipated in the long run with energy patterns returning to those seen before the oil crisis. Podobnik notes that "by the 1980s most industrial countries had returned to energy consumption patterns that were reminiscent of the early 1970s. Reliance on imported oil and gas resources had again intensified, while few viable alternatives to fossil fuels were under development" (38, p. 141). This was symbolically represented by Ronald Reagan's explicit commitment to energy abundance through oil in his successful 1979 US election campaign, which saw the deprioritizing of energy conservation and renewables that had been promoted by President Jimmy Carter. This is recognized by historians as a notable return to abundance (62). Government spending on oil continued to outweigh that spent on energy efficiency or renewables after the oil crisis. As Mitchell highlights (75), ultimately conditions of scarcity and reduced demand rather than threatening oil incumbents led to regime adaptations and changes in strategy, including prospecting for oil in new locations and exploiting natural gas. Similarly, Auzanneau (46) points toward incremental innovations in the oil regime that enabled further extraction of oil resources but at a higher price. New oil fields in Alaska and the North Sea became a priority. While in the 1970s nuclear production had quadrupled and replaced oil in some electricity systems, such as in France and the Netherlands, this however only replaced 5% of oil consumption, mainly in the electricity sector (39).

At the meso-level, the rules that manifested during the oil crisis dissipated as the system returned toward an imperative to use oil and maintain abundance and constant supply. Similarly, electricity systems and regulation continued to be centralized, and the transatlantic zone remained dependent on international oil imports (46). There was also a restructuring of the oil industry with OPEC nations in a stronger position and the emergence of national oil companies, yet this did not lead to a significant long-term change in patterns of oil consumption. However, what is evident in the literature on the aftermath of the oil crisis is the diversity of responses and efforts in regard to the crisis. In countries such as Denmark and later Germany, demand reduction became a key feature of energy policy from the late 1970s, representing niche spaces in the transatlantic zone where renewables were strongly supported. California was another such location. This more decentralized approach to energy differs from the diversity of supply pursued by France, reliant on centralized nuclear power. The cases of Denmark and Germany highlight what is referred to as critical antecedents, social movements, and particular long-term cultural factors that contributed to the sustaining of renewable niches and energy efficiency in these countries (76). Niche spaces in other countries like the United States and the United Kingdom persisted in the form of research departments that also maintained awareness of the importance of demand reduction and diversifying supply away from fossil fuels, although these rules had decayed at the meso-level (38).

5. Discussion

Shocks are an important driver for change in the MLP. They are mainly conceptualized as WoO. In this paper, we have explored imprinting as another and a complementary way of conceptualizing shocks. We have explored two shocks, WWII and the 1973 oil crisis, from the perspective of imprinting, expecting that this conceptualization would allow us to explain the impact of the WWII shock but not the oil crisis. This expectation has been confirmed. What we found is that WWII is a good fit with imprinting theories. The four mechanisms of change are clearly present: new demand pressures were felt, the energy system was redirected in order to support the war, new policy capacities were put in place, and constraints on energy provision were accepted as a shared sacrifice. These mechanisms put new conditions in place across the transatlantic zone, resulting in the imprinting of new rules, including the imperative to use oil, the focus on maintaining abundance and constant supply, and a move toward centralization and internationalization. These new rules continued to shape the development of the energy system up to the oil crisis.

With regard to the oil crisis of 1973, we also see the imprinting mechanism beginning to operate. There was a discussion of rapid change in rules, away from a system geared around abundant oil to a new condition of scarcity and the need to reduce demand. The imperative to increase indigenous supply and diversify energy sources also became more prominent. However, we highlight how commitments to fossil fuel abundance took prominence once again at the end of the 1970s, and demand reduction became generally deprioritized compared to its prominence during the crisis. New policy capacities emerged, in particular, the establishment of the IEA, yet, this actor did not push for the further development of the new rules. Finally, the language of common sacrifice was used but did not unite actors. What did happen is that alternative rules were developed in niche spaces, with some policy protection for varying degrees of time in terms of R&D programs for renewables.

The divergence of responses across the transatlantic zone after the oil crisis compared to the shared stability in the energy regime after WWII suggests that the former shock should be treated as a window of opportunity, in which niche actors managed to promote particular agendas. The shock did not cause the imprinting of new rules on regime actor behavior. We would like to suggest that this difference may be a result of the duration of the shock and the extent of devastation in the form of physical destruction, violence, and tragic loss of life. A relative fast return to normal conditions may undo emerging imprinting. Actors responded strategically to the challenges driven by the shock and discussed how to respond but never changed the rules they were using before the oil crisis. In this case, critical antecedents that existed prior to the shock shaped the strategic action of regime actors. In fact, these critical antecedents were the rules put in place by WWII.

We argue that imprinting can be a useful additional concept in the exploration of the role of shocks in sustainability science. It brings into view that shocks are not just a new WoO to be exploited by actors but may bring fast institutional change partly due to traumatic experiences, inviting sustainability to take into account emotional experiences, and psychological consequences of shocks. Whether shocks induce a process of imprinting or act as WoO will shape their consequences. In the former case, a shock will induce institutional (rules and thus regime) change leading to immediate system change with long-term and irreversible consequences. In the latter case, a shock can also contribute to system change if niche-innovations are sufficiently developed but may take longer since regime actors need to open up for investing in the deployment of niche-innovations, accepting that the prevailing regime needs a fundamental change.

Our analysis invites a discussion of shocks in the context of contemporary events. In 2022, we are living through a shock to the energy and food systems due to a war in Ukraine. Should we treat this shock as a window of opportunity or a case of imprinting? What is clear is that the war has put in place some of the conditions that may lead to imprinting, but they are emerging and may be stalled again. There is demand pressure in terms of high gas prices and reduced gas exports from Russia to Europe and higher food prices and interruption of the global food supply chains; there is a change in directionality, in which all European countries are calling for ways to reduce dependence on international energy supplies and encouraging demand reduction measures for winter 2022; new policy capacities are emerging, as all European countries have intervened in exceptional ways to cap energy prices to protect consumers, alongside the EU agreeing a plan of action to reduce dependence on Russian oil and gas. However, a substantial shared sacrifice is not yet emerging because the shock did not lead yet to a severe devastation (in Western European countries) comparable to the Second Word War. Our conclusion is that the Ukraine war and related energy and food provision shocks have not yet led to a larger regional or global imprinting process and are better seen as a WoO (except for Ukraine).

The present war and ensuing energy and food crises raise another question: whether shocks will influence change in a sustainable or unsustainable direction? On the one hand, there is evidence that the stronger entwinement of energy with national security concerns will lead to an acceleration of use of renewables with the latest IEA analysis highlighting that the crisis has "turbo charged" clean energy transitions (77). However, on the other hand, a temporary increase in fossil fuel use is expected too and there is a significant risk that the construction of new gas infrastructure, built to gain independence from Russian gas supplies, could deepen and/or extend a fossil fuel lock-in (78). A rule that focuses on keeping significant gas and oil supplies in place may become imprinted into the energy regime through, for example, the extending of relationships for the supply of Liquified Natural Gas and construction of new gas infrastructure.

A final key point for consideration concerns the duration of a shock. What is suggested by our case studies is that a longer duration will make imprinting more probable. We would like to argue that this duration effect can also come from an accumulation of shocks. The Ukraine war happened in the context of another shock: the COVID-19 pandemic. Many expressed the hope that the pandemic would be an opportunity for rapid shifts toward sustainability since it showed that governments can intervene and develop new policy capacities (78). Yet, as is the case for the Ukraine war, it can be questioned whether change is moving in a sustainable direction. There is no substantial evidence that the COVID-crisis by itself has led to imprinting and thus rule change in the energy system (79). However, this does not necessarily mean that the COVID shock will not contribute to such a process in combination with the Ukraine war shock, and other shocks related to the climate crisis. It is expected that climate shocks will increase in frequency and intensity and thus sustainability transitions will increasingly be shaped by such events. This observation suggests that future research should not just look at individual shocks but also at how several shocks interact with each other, assuming they may reinforce each other or work in different directions.

The effect of shocks through imprinting and windows of opportunity will likely become increasingly important in future developments. The field of sustainability science was conceived during

a time of relative stability in the transatlantic zone; however, this period is now widely considered to be over. Indeed, the North Atlantic Treaty Organisation (NATO) sees the next few decades as one of increasing "strategic competition, pervasive instability and recurrent shocks" (80). Extreme weather events including floods and droughts, consequent disruption of food supplies, a lingering energy crisis, increased risk of hybrid warfare including cyber-attacks, terrorist attacks, new geopolitical tensions between global powers leading to war, global economic instability leading to financial crises, and increased risk of future pandemics influenced by a warming climate, are shocks that security agencies and militaries are seeing as being more prevalent in an age of pervasive instability. Shocks are unpredictable, but it is likely they will become more pertinent for understanding directionality in sustainability transitions as their frequency increases. Indeed, the past few years demonstrate that it may be wise to follow the well-known maxim attributed to Oscar Wilde: expect the unexpected. Shocks may become the new normal, closing down or opening up specific transition pathways. These may be pathways that were perceived as impossible. For example, ones that put a lot of emphasis on energy saving, frugality and localization but also ones that lead to an intensified search for and massive deployment of geo-engineering and carbon capture and storage technologies. Accordingly, sustainability science will need more research on the role of shocks in sustainability transitions.

Data, Materials, and Software Availability. All study data are included in the main text.

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