Publizierbarer Endbericht

Gilt für Studien aus der Programmlinie Forschung

A) Project data

General overview	
Short Title:	TIMELAG
Long Title:	Time lags in transformative processes: Temporal dynamics between policy design, implementation and market diffusion of low carbon technologies
Citation:	Kulmer, V., Seebauer, S., Haas, W., Theurl, M. (2020). Time lags in transformative processes: Temporal dynamics between policy design, implementation and market diffusion of low carbon technologies. Final project report to the Austrian Climate and Energy Fund, Austria.
Research program (year):	ARCP 9th Call 2016
Duration:	01.03.2017 bis 31.12.2019
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Project and cooperation partners (incl. federal state):	Institut für Soziale Ökologie, Universität für Bodenkultur (Wien), formerly assigned to Alpe-Adria Universität Klagenfurt
Keywords:	Turning points in market diffusion, low carbon technologies, multiple streams approach, Change Point analysis
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General overview	
Klimafonds-Nr:	KR16AC0K13343
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B) Projektübersicht

1 Kurzfassung

Motivation und Projektziele

Der Klimawandel erfordert unter anderem eine rasche Marktdurchdringung energieeffizienter, kohlenstoffarmer Technologien anstelle von auf fossilen Brennstoffen basierenden Produkten. Die Identifikation und Analyse gesellschaftspolitischer und technologischer Prozesse zur Stimulation des Marktwachstums, ist ein Grundpfeiler von zukünftigen Transformationspfaden. Das reale Marktwachstum innovativer Technologien ist in der Regel kein kontinuierlicher Prozess, sondern durch wechselnde Phasen der Beschleunigung, Stagnation oder Verzögerung gekennzeichnet. Daher sind gezielte politische Maßnahmen erforderlich, um Wendepunkte für eine beschleunigte Marktverbreitung kohlenstoffarmer Technologien auszulösen oder zu ermöglichen.

TIMELAG untersucht die zeitliche Dynamik der Marktdiffusion kohlenstoffarmer Technologien anhand der drei Technologien Elektroautos, Wärmepumpen und Photovoltaik. Die Analyse dieser drei Fallbeispiele zeigt auf, wie die Marktdiffusion klimafreundlicher Technologien künftig beschleunigt werden kann. In diesem Sinne trägt TIMELAG zur Diskussion über Dynamik und Geschwindigkeit der Technologiediffusion bei.

Methode

Zur Bestimmung und Erklärung der Wendepunkte wurden in einem mehrstufigen, interdisziplinären Ansatz quantitative und qualitative Forschungsmethoden kombiniert. Theoretisches Rahmenwerk sind die *Diffusion of Innovations* Theorie (Rogers 1983) und der *Multiple Streams* Ansatz (Kingdon 1984).

Zunächst wurden mittels *Change Point* Analyse historische Marktdaten mit der klassischen logistischen S-Kurve der Diffusion von Innovationen verglichen, welche die Nullhypothese der Analyse bildet. Die Grundlage dieser Analyse bildeten dabei robuste und validierte Daten einer kontinuierlichen Zeitreihe zur Marktdiffusion von Photovoltaik, Elektroautos und Wärmepumpen, die von WP3 bereitgestellt wurden. Die *Change Point* Analyse – die Kernaktivität in WP5 – testet eine Reihe mathematischer Modelle alternativer Wachstumsfunktionen und Wachstumsparameter, wie gut sie die beobachteten Zeitreihen abbilden können. Es wurden jene Kalenderjahre bestimmt, in denen Wendepunkte bei der Marktdiffusion auftraten.

Im zweiten Schritt wurden mittels eingehender Dokumentenanalyse und qualitativen ExpertInnen-Interviews gesellschaftspolitische und sozio-technologische Entwicklungen im Zusammenhang mit der Marktdiffusion rekonstruiert und als Abfolge kritischer Ereignisse in den Strömen *Politics*, *Policy* und *Technology* dargestellt. Für jede Technologie wurden historische Eckpfeiler und kritische Ereignisse auf einer Zeitschiene von 1970 bis heute festgelegt. Diese

Zeitschienen bildeten den Ausgangspunkt für den in WP4 verwendeten *mixed-method* Ansatz, der eine kompakte Auswahl kritischer Ereignisse ableitete.

Im dritten Schritt wurde für jede Technologie die Abfolge kritischer Ereignisse in den drei Strömen zu einem konsistenten Handlungsstrang integriert. Mithilfe der Handlungsstränge wurde erklärt, wie Wendepunkte aus dem Kulminieren kritischer Ereignisse oder aus einer Verkopplung der Ereignisse in allen Strömen entstanden. Die Verknüpfung der mathematisch ermittelten Wendepunkte mit den zugrundeliegenden kritischen Ereignissen wurde im Rahmen eines Stakeholder Workshops in WP6 validiert.

Im vierten Schritt wurde mittels einer Befragung zur Abfolge und Dauer von Renovierungsarbeiten an Wohngebäuden auch die Perspektive der EndverbraucherInnen berücksichtigt. Die in WP5 durchgeführte Befragung erweitert die bestehende Literatur um die systematische Analyse unterschiedlicher kritischer Ereignisse auf die Umsetzung und Geschwindigkeit von Renovierungsarbeiten.

Der mehrstufige, interdisziplinäre Forschungsansatz bringt auf der einen Seite die Diskussion über Dynamik und Geschwindigkeit der Technologiediffusion voran. Dies ist vor allem für erweiterte Szenarienanalysen und Prognosemodelle von großer Relevanz (van der Kam et al. 2018, Harris et al. 2018). Auf der anderen Seite demonstrieren wir die Anwendung einer systematischen Methode mit dem Ziel vergangene Entwicklungen zu erklären, um zukünftige Bestrebungen zur Steuerung der Technologiediffusion lenken zu können.

Zentrale Erkenntnisse

Unsere Ergebnisse zeigen, dass real beobachtete Diffusionsprozesse zu bestimmten Zeitpunkten ihre Richtung und Geschwindigkeit ändern, anstatt der idealtypischen S-Kurve der Technologiediffusion zu folgen. Klimaziele in Kombination mit verbindlichen Vorschriften sind zentrale Hebel, müssen jedoch von Maßnahmen in den Strömen *Politics*, *Policy* und *Technology* begleitet werden. Zum Beispiel liefert der technologische Fortschritt durch F & E-Programme, Produktentwicklung und Qualitätskennzeichnungen einen notwendigen Impuls, wie die Marktdiffusion der Wärmepumpe in den 1980er-2000er-Jahren zeigt. Aktivitäten in Nachbarländern und globale Einflüsse spielen eine komplementäre Rolle. Dies wird durch die positive Auswirkung der deutschen Gesetzgebung zu erneuerbaren Energien auf die österreichischen PV-Förderprogramme, das internationale DACH-Label zur Gewährleistung der Wärmepumpenqualität und die chinesischen Emissionsobergrenzen von PKWs, die verbindliche Flottenstandards in Europa ermöglichten, unterstrichen.

Daneben treiben unspezifische Förderprogramme die Marktdiffusion kohlenstoffarmer Technologien nur unzureichend voran. Positive Wirkungen sind oft auf Vorzieh-Effekte beschränkt, wie der vorübergehende Anstieg bei E-Autos durch die Mobilitätsregionen zeigt. Das Beispiel PV zeigt die kontraproduktive

Wirkungen von Förderungen, da die laufenden Änderungen und Kürzungen in den Förderungen zu großen Unsicherheiten geführt haben.

Schlussfolgerungen

Das stetige Beobachten der gesellschaftspolitischen und sozio-technischen Entwicklungen in den Strömen *Politics*, *Policy* und *Technology* ermöglicht das Erkennen von Marktdiffusionsbarrieren einerseits und das Antizipieren günstiger Zeitpunkte zur Beschleunigung der Marktdiffusion andererseits. Maßgeschneiderte politische Interventionen erfordern jedoch eine reflexive und adaptive politische Integration, sowohl horizontal über Wirtschaftssektoren, Politikbereiche und Technologien als auch vertikal von lokaler zu überregionaler Ebene. Schließlich sollten Maßnahmenbündel nicht auf eine maximale Marktdurchdringung drängen, sondern ein optimales Zusammenspiel komplementärer Technologien anstreben, die gemeinsam zur Reduzierung der Treibhausgasemissionen und zur Erreichung der Nachhaltigkeitsziele beitragen.

2 Executive Summary

Project rationale and objectives

Climate change calls, among other actions, for rapid market penetration by energy-efficient, low-carbon technologies that substitute fossil-fuel powered products. There is a need for identifying and analyzing socio-political and technological processes stimulating market growth in order to design transformative pathways. Real-world market growth of innovative technologies is typically not a continuous process, but characterized by intermittent phases of acceleration, stagnation or even relapse. Thus, targeted policy actions need to identify and explain turning points of accelerated market diffusion of low-carbon technologies. On a wider note, the TIMELAG project strives to advance the discussion on dynamic and pace of technology diffusion.

Methodology

In a mixed-method, multistep approach we identified and explained turning points by integrating Diffusion of Innovations Theory (Rogers 1983) with the Multiple Streams Approach (Kingdon 1984):

First, the mathematical technique of change point analysis compared historical market data to the baseline s-shape to determine the calendar years when turning points in market diffusion occurred. Therein, robust and validated continuous time-series data on market diffusion of photovoltaic, electric cars and heat pumps provided by WP3 built the basis of the mathematical change point analysis. The latter was a core activity in WP5, where a range of change point models, comprising alternative growth functions and parameters, were tested against the observed market data.

Second, document analysis and deliberation with experts reconstructed socio-political developments related to market diffusion as a sequence of critical events

in the politics, policy and technology stream. To that end, in WP2, by means of an in-depth review for each considered technology, historical cornerstones and critical events on a timeline from 1970 to the present were established. These timelines built the foundation of the mixed-method approach employed in WP4 narrowing down to a compact selection of critical events.

Third, sequence of critical events in the politics, policy and technology stream were integrated into storylines to explain in hindsight how turning points emerged from continuous buildup or critical junctures between the three streams. In WP6, the turning points determined in change point analysis and the critical events underlying these turning points were scrutinized and validated in a stakeholder workshop.

Fourth, in order to account for the bottom-up consumer-level perspective an empirical survey on sequences of residential renovation activities was conducted. The survey expands on the previous literature by systematically testing the differential impacts of a broad scope of critical events on several renovations, thereby highlighting that critical events do not uniformly apply to all kinds of renovations.

By doing so, on the one hand, we advance the discussion on dynamic and pace of technology diffusion, which is particularly important for advanced scenario analysis and forecast models (van der Kam et al. 2018, Harris et al. 2018); on the other hand, we demonstrate a systematic methodology for understanding past developments in order to inform future diffusion efforts.

Main Findings

Our results reveal that observed diffusion processes change direction and pace at specific moments in time, rather than following a uniform s-shape. Carbon emission reduction targets combined with mandatory regulations are key levers, but need to be accompanied by actions in the politics, policy and technology stream. For instance, technological advancement from R&D programs, product development and quality labels provide necessary impulses, as in the case of heat pumps from the 1980s to 2000s. Neighboring countries and global influences play a complementary role, as underscored by the positive spillover of German renewable energy legislation on Austria’s PV funding schemes, the international DACH label ensuring heat pump quality and Chinese fuel consumption standards enabling mandatory fleet standards in Europe.

Unspecific subsidy programs appear to be less effective for advancing diffusion of low-carbon technologies. The diffusion impact of Austrian subsidy programs seems constrained to pull-forward effects, as in the temporary sales boost from the e-mobility regions scheme, or to fueling adoption in a restricted customer segment, as the photovoltaics segment response to feed-in tariffs and investment grants might have been saturated within a few years.

Conclusions

Continuously monitoring all streams may allow to detect barriers of market diffusion or to anticipate upcoming windows of opportunity when streams converge and targeted action could trigger accelerated growth. Yet, such tailor-made policy interventions require reflexive and adaptive policy integration; both horizontally across economic sectors, policy spheres and technologies and vertically from local to supra-regional levels. Finally, policy mixes should not push for maximum market penetration but seek an optimal interplay of complementary technologies jointly contributing to carbon emission reduction and reaching emission targets.

3 Motivation and objectives

The necessity to transform the Austrian transport and energy sector towards less carbon emissions is well known. The (potentially) effective policies to bring about this transformation are equally well understood (APCC 2014, UBA 2015, WBGU 2011). Eventually, in some decades, market forces and pressure from limited resources alone will lead to a replacement of conventional, fossil-fuel based technologies by their innovative, low carbon substitutes. However, relying just on slow self-regulatory transformation will incur substantial social and ecological costs (Stern 2006, Steininger et al. 2014). Consequently, there is a need for identifying and analyzing the main socio-political and technological processes stimulating market growth in order to design transformative pathways to reach the targets of + 1.5°C or +2°C global warming (IPCC 1.5 ° Special Report). This calls for an in-depth understanding of the dynamics in the market uptake of low-carbon technologies, in particular its discontinuities and acceleration/deceleration phases, in order to identify potential policy avenues for speeding up transformation.

Real-world market growth of innovative technologies is typically not a continuous process, but characterized by intermittent phases of acceleration, stagnation or even relapse. Many diffusion research and forecast models build on Diffusion of Innovations Theory (Rogers 1983) which posits that the cumulative number of adopters follows an s-shaped curve. The s-shape involves two turning points when the diffusion dynamic changes direction: the take-off point when slow initial uptake by early adopters turns to rapid diffusion among mass consumers; and the saturation point when diffusion levels off as only laggards remain to enter the market (van der Kam et al. 2018, Gnaan et al. 2018). Turning points do not appear randomly, but trace back to developments and critical events in, for instance, investment and operating costs, characteristics of the technology, popularity, policy measures, social aspects and infrastructure (Lee et al. 2012, van der Kam et al 2018, Simpson and Clifton 2016, Changgui et al. 2018).

TIMELAG reconstructs the evolution of low carbon technologies and of various types of influences aiming to promote their market uptake along a time line, visualizing their interrelations. The **objective of TIMELAG is to identify and explain turning points in the market diffusion of low-carbon technologies**. We do so by employing an integrative, interdisciplinary approach, combining qualitative and quantitative methods. *First*, the mathematical technique of change point analysis compares historical market data to the baseline s-shape (Roger 1983) to determine the calendar years when turning points in market diffusion occurred. *Second*, drawing on Kingdon's Multiple Streams Approach (1984), document analysis and expert interviews reconstruct socio-political developments as a sequence of critical events that can be regarded as required precursors for an accelerated market diffusion. Both methods are compiled to explain in hindsight how turning points were made possible by the coincidence of emerging windows of opportunity in all three streams, the politics, policy and technology stream. *Third*, in order to account for the underlying individual and interpersonal processes, a survey among accomplished adopters of low carbon technologies contrasting how strongly interpersonal diffusion, discounting heuristics and specific policy measures influence the speed of market uptake in this population segment.

We analyze the diffusion of three low-carbon technologies in Austria from 1970 to 2018: privately owned electric vehicles, photovoltaics panels, and heat pumps for residential space heating. These are large-purchase technologies where mature products are available on the market. They are (still) in the early stages of market penetration long before consolidation to a saturated, stabilized market share. While our results only reflect the context of Austria as a typical developed country, we expect that our methodology may be replicated in other countries or with other technologies.

4 Content and results

The results of five interlocking work packages feed into the main findings and conclusion of TIMELAG (as illustrated in Figure 1): WP3 provided robust and validated continuous time-series data on market diffusion of photovoltaic, electric cars and heat pumps building the basis of the mathematical change point analysis. The latter was a core activity in WP5, where a range of change point models were tested against a basic diffusion curve and turning points in the market diffusion of technologies were identified. Additionally in order to account for the bottom-up consumer-level perspective, an empirical survey on sequences of residential renovation activities was conducted. In WP2, by means of an in-depth review for each considered technology historical cornerstones and critical events on a timeline from 1970/1990 to the present were established. These timelines built the foundation of the mixed method approach employed in WP4 narrowing down to a compact selection of critical events. WP6 synthesized, scrutinized and cross-checked the critical (WP4) events selected to determine the turning points (WP5).

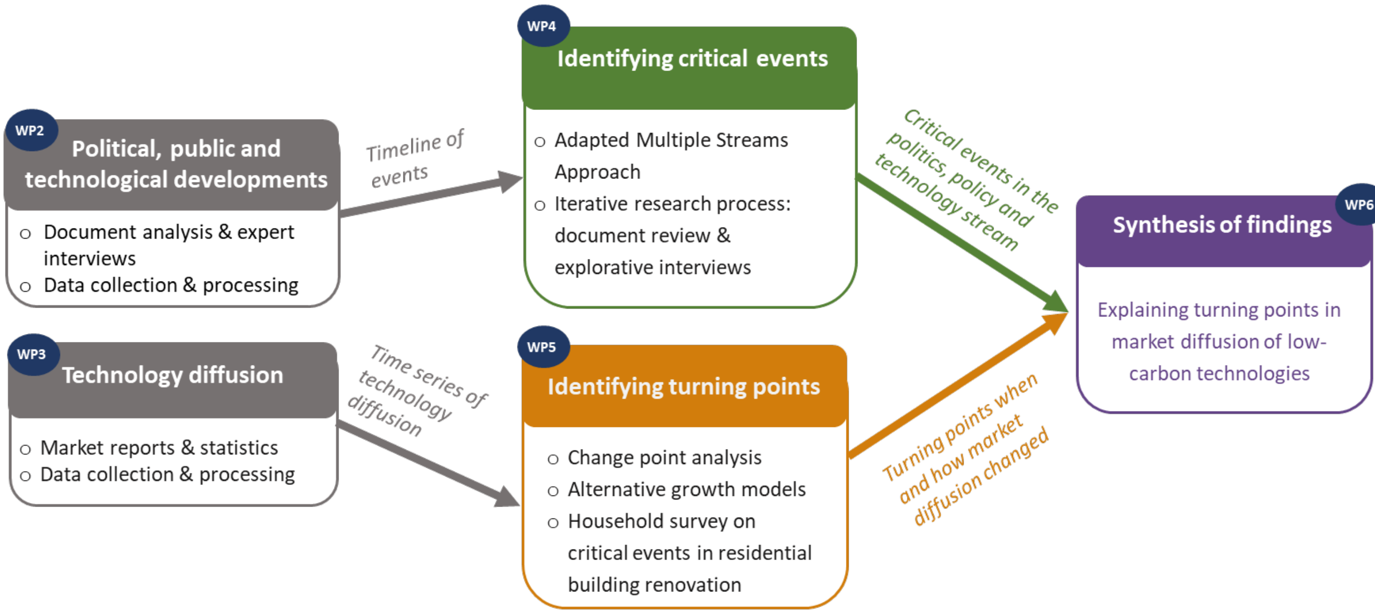


Figure 1: Overview of the project workflow

Timelines of politics, policy and technology stream (WP2)

As indicated in Section 6, 466 documents, comprising European and national policy strategies, environmental assessment and climate monitoring reports, reviews on technological and market progress, as well as major policy programs and regulation, were analyzed in order to identify outstanding events in the different streams of each technology. Moreover, several climate and energy policy documents addressed all three technologies. The identified events were placed on a timeline and comprised 128 events related to electric cars, 79 events related to heat pumps and 102 events regarding photovoltaics, with each event assigned to either the politics, policy or technology stream.

Table 1 illustrates the chronological timeline of events related to heat pumps in each stream from 1950 to 2018.

Table 1. Chronology of events in technology, policy and politics streams of heat pumps

Year	Description of event	Stream
1950s	Low commodity and oil prices	Politics
1970	Internationally regarded as year of actual modern environmental policy	Politics
1972	United Nations Conference on the Human Environment in Stockholm	Politics
1972	Foundation of the Federal Ministry of Health and Environmental Protection	Politics
1973	1st Oil Crisis: Opec Arab states (OAPEC) cut off the West from their oil supply	Politics
1975	**Austrian Energy Plan**	Politics
1976	**Revision of the Austrian Energy Plan**	Politics
1978	**Subsidy program for newly installed heat pumps**	Policy
1978	**Taskforce analyzing heat pumps**	Politics
1979	**2nd Oil Crisis**	Politics
1979	Austrian Energy Report	Politics
1979	**Rising oil prises**	Technology
1980	**R&D heat pump funding program**	Policy
1980	**Provincial heat pump subsidies**	Policy

1980	Regulation concerning the reduction of energy loss and energy consumption of central heating	Policy
1984	Federal Act on comprehensive protection of the environment	Policy
1984	Occupation of the Hainburger Au	Politics
1985	Villach Conference	Politics
1985	Environmental Control Act	Policy
1985	Establishment of the Austrian Environment Agency (based on the Environmental Control Act)	Policy
1985	**Global collapse of heat pump sales (negative public opinion)**	Technology
1985	Vienna Convention for the Protection of the Ozone Layer	Politics
1986	Chernobyl nuclear disaster	Politics
1987	Montreal Protocol on Substances that Deplete the Ozone Layer	Politics
1988	14^{th} G7 summit in Toronto: Developed countries voluntarily agree to cut carbon dioxide emissions by 20% by 2005	Politics
1988	Foundation of the Intergovernmental Panel on Climate Change (IPCC)	Politics
1989	**Geothermal heat pumps recorded in market statistics**	Technology
1990s	**Continuous technological improvements**	Technology
1990s	Foundation of the National Carbon Dioxide Commission	Politics
1992	United Nations Conference on Environment and Development in Rio de Janeiro	Politics
1992	Introduction of the EU-Ecolabel	Policy
1993	Environmental Support Act	Policy
1995	Austria joins the European Union	Politics
1995	**Mineral oil tax aligned with EU standards, tax increase of 50%-150%**	Policy
1995	**Law prescribing minimum energy efficiency of new buildings**	Policy
1996	First law to introduce taxes on natural gas, 60 Groschen/m3	Policy
1996	First law to introduce taxes on electricity, 10 Groschen = 0,7 cents/ kWh	Policy
1997	Kyoto-Protocol: Austria commits to reduction of GHG emissions of 13% in 2008-2012 compared to 1990 levels	Politics
1998	Electricity Business and Organisation Act - enters into force 1999	Policy
1998	**Establishment of the DACH quality label for heat pumps**	Politics
1999	Launch of the Kyoto Forum	Politics
1999	Environmental Control Act 1998 enters into force	Policy
2000	Energy Liberalization Act comes into force 2002	Policy
2000	Tax rate on electricity increased to 1.5 cents/kWh (previously 0.7 cents/ kWh)	Policy
2000	Strong market growth of heat pumps	Technology
2001	Complete liberalization of the Austrian electricity market	Politics
2001	Austrian Energy Regulatory Authority ("E-Control") takes up activities	Politics
2002	**EU Directive, minimum energy performance of buildings**	Policy
2002	Austrian Climate Strategy for achieving the Kyoto target	Politics
2002	EU Directive with regard to energy labelling of household air-conditioners	Policy
2002	Green Electricity Act comes into force 2003	Policy
2004	EU Directive with regard to energy labelling transposed into Austrian law	Policy
2004	Federal Act establishing a scheme for greenhouse gas emission allowance trading	Policy
2005	**Acquisition costs fall by a factor of 1.5 to 1990**	Technology
2005	Adoption of the Montreal Action Plan (Montreal Climate Change Conference)	Politics
2005	Kyoto-Protocol enters into force	Politics
2006	**Provinces agree on harmonized energy efficiency requirements**	Policy

2007	Federal Act on the Climate and Energy Fund	Policy
2007	**Harmonized building guidelines for efficient heating and construction**	Policy
2008	**Climate and Energy Fund starts funding program for building renovation**	Policy
2009	EU Directive 2009/28/EC on the promotion of use of renewables: Austria: share of renewable energies in total energy consumption 34% by 2020	Policy
2009	**EHPA European quality label replaces DACH label**	Politics
2009	Strong subsidies for oil boilers by the Austrian Mineral Oil Industry from 2009 to 2019 (counter-effective)	Policy
2009	Extension to Agreement FLG II No 19/2006 that go beyond the minimum standards	Policy
2010	**EU building guideline revision "zero emission building"**	Policy
2011	**Building guidelines revised "to meet zero-emission target 2020"**	Policy
2011	Refurbishment program "Sanierungsoffensive" starts	Policy
2011	Fukushima Daiichi nuclear disaster	Politics
2011	Germany decides to phase out nuclear energy production for good by 2022	Politics
2011	Climate Change Act enacted	Policy
2012	EU Directive 2012/27/EU (Energy Efficiency Directive, EED) enters into force	Policy
2014	Energy Efficiency Act, Transposition of EED into national law	Policy
2015	UN Climate Conference in Paris (Cop21)	Politics
2015	Ban of oil heating in several provinces	Technology
2016	Greenbook for an integrated climate and energy strategy	Politics
2016	Electricity Regulation 2016, all grid operators obliged to report the PV capacity installed in their grids to E-Control	Policy
2017	Regulation (EU) 2017/1369 setting a framework for energy labelling (repealing directive 2010/30/EU)	Policy
2018	From 2018 onwards: "Sanierungsoffensive" & "Raus aus dem Öl" subsidy for the exchange of oil boilers against alternative energy source	Policy

For reasons of brevity, the timelines of events, with each assigned to either the politics, policy or technology stream, regarding photovoltaics and e-car are reported on the project website (https://timelag.joanneum.at/results).

Vectors of technology diffusion (WP3)

WP3 researched, annotated and cross-checked a database with indicators illustrating the market uptake of three low carbon technologies: (1) electric vehicles, (2) photovoltaics panels, and (3) heat pumps. Heat pumps were selected over other renewable residential heating systems, as solar overlaps with water heating, and biomass is too diverse in terms of burned fuels (solid, chips, pellets, etc.) to allow conclusive analyses. The TIMELAG database on market diffusion of the respective technologies contains numerous indicators for each technology, with a spatial resolution at the provincial level and a temporal resolution of annual as well as biannual data points over a timespan of (mostly) several decades. Figure 2 provides an overview of the structure of the TIMELAG database.

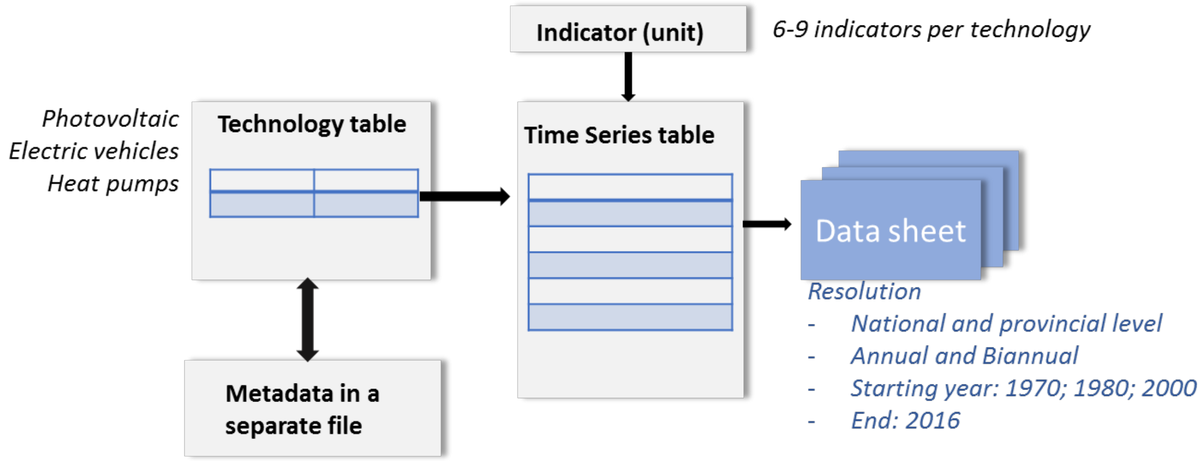


Figure 2 Overview of TIMELAG Technology database

To the best of our knowledge, the TIMELAG database includes all valid statistical information currently available in Austria on the historical market diffusion of the three low carbon technologies. However, these data underlie particular shortcomings and only a few were sufficient in terms of consistency and reliability for change point analysis. By means of technical reports describing generation of the used data, research studies applying these data for analysis and expert interviews in WP4, inherent data limitations of the respective time series were assessed and interpretations from the descriptive and statistical analyses (WP3) of these data were verified. The in depth investigation of the collected data highlighted that most data sources for technology vectors are in part inconsistent or contradictory, in particular in the case of residential heat pumps and photovoltaics. We consulted experts involved in the collection or processing of the respective data, in order to gain a better understanding of the reasons leading to biased data, and to develop mitigative strategies. The intensive investigation into data validity was summarized for the case of photovoltaics diffusion in the following trade journal article (see Box below).

Frieden, D., 2019, Verfügbarkeit und Qualität von Photovoltaikanlagen-Statistiken in Österreich? *Sonne, Wind und Wärme*, Heft 15/ 2019,

Abstract. *Aggregierte Statistiken zum Ausbau der Photovoltaik in Österreich sind hinlänglich bekannt und reichen aus, um die allgemeine Marktentwicklung einzuschätzen. Kommt es jedoch auf detaillierte Auswertungen zur Marktdurchdringung in Privathaushalten an, ist die Datenlage begrenzt. Österreich verfolgt wie andere europäische Staaten ambitionierte Ziele zum Ausbau der Photovoltaik (PV). Für vorausschauende Planung und politische Steuerung ist ein klares Bild der Marktdiffusion notwendig. Die PV-Adoption in Privathaushalten ist von besonderem Interesse, da diese eine Grundlage für die breite Akzeptanz und Ausrollung der Energiewende darstellt. Eine konsistente Zeitreihe des Ausbaus von PV-Kleinanlagen bis 5kWp als Annäherung für Privathaushalte ist jedoch nicht verfügbar. Stattdessen existieren diverse Datenquellen deren Konsistenz, Komplementarität sowie wissenschaftliche Nutzbarkeit im Folgenden besprochen werden.*

In the course of the in-depth screening of the TIMELAG database, the following data were selected to be best suitable to study technology diffusion in Austria and hence be applied to change point analysis: the stock of e-cars in Austria from 1990 to 2018 documented by the vehicle registration statistics document (Statistics Austria 2018). The annual report on innovative energy technologies in Austria (Biermayer et al. 2019) states the number of heat pumps for space heating from 1970 to 2018 and the market development of installed photovoltaics capacity in kWp from 1990 to 2018; this report aggregates annual reports of industry associations, annual accounts of major firms, market research and surveys among distributors, retailers as well as operators. To the best of our knowledge, Biermayr et al. (2019) currently provide the best market coverage on heat pump and photovoltaics diffusion in Austria (Frieden 2019).

Turning points in market diffusion (WP5)

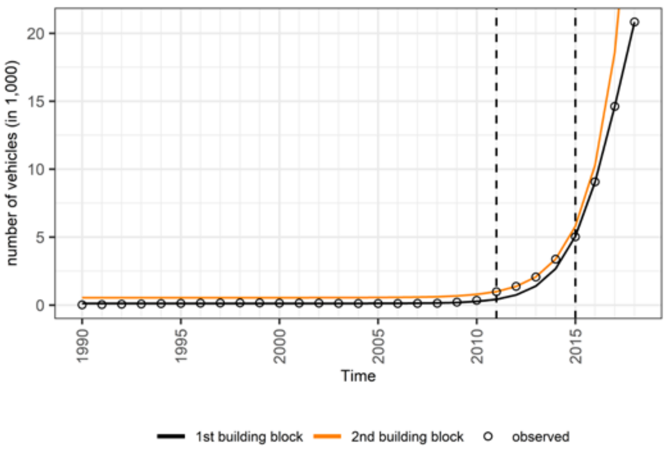
The mathematical technique of change point analysis compares historical market data to the baseline s-shape to determine the calendar years when turning points in market diffusion occurred. More precisely, as posited by diffusion of innovations theory (Rogers 1983, see Section 5) the null hypothesis of this study states that technology diffusion follows an s-shaped logistic function (baseline model). For each low-carbon technology, Table 2 reports the corrected Akaike information criterion (AICc) for the baseline model and for the best-fitting model of each class of alternative Turning Point (TP) models. None of the investigated technologies adheres to the s-shape presumed by theory; hence, the null hypothesis is rejected throughout. According to the AICc values, for electric vehicles (EV) the two TP model and for photovoltaics (PV) and heat pumps (HP) the discrete TP model show the best fit. In contrast to theory, the smooth TP model performs worst among all alternative models in all technologies, as observed market diffusion fluctuates.

Table 2 Model selection: AICc and years of turning points for the baseline and best-fitting variation of alternative models for electric cars, heat pumps and photovoltaics panels

	Electric cars		Heat pumps		Photovoltaics	
	AICc	Turning point	AICc	Turning point	AICc	Turning point
Baseline model	384	-	893	-	686	-
Best-fitting discrete TP model	353	2010, 2014	**739***	**1985, 2005**	**545***	**2004, 2014**
Best-fitting smooth TP model	354	2009, 2015	754	1990, 2005	552	2004, 2013
Best-fitting two TP model	**322***	**2011, 2015**	778	1981, 2004	604	2001, 2013

*Selected model (best fit according AICc)

Change point analysis offers the double advantage of identifying points in time (i) *when* and (ii) *how* the pace and dynamic of diffusion change. Comparing the alternative models between the technologies reveals some striking differences. The year of the change point and the ensuring reorientation in the shape of the curve informs on the occurrence of accelerate and brake effects.



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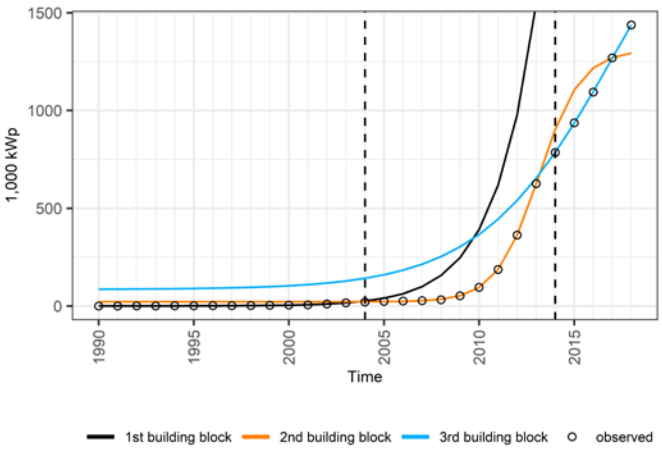
Electric vehicles started to take hold in the vehicle market in 2011, when market performance changed to a phase of rapid growth (modelled as an exponential function). This stark growth phase was quite short and lasted until 2015, when the pace of growth decreased and returned to the logistic function of the first building block[1]. The period between 2011 and 2015 seems to represent a pull forward effect, where the market development deviates only for a limited period from the underlying trend. Still, post-2015 the number of vehicles continues to grow fast, but seems to level off.



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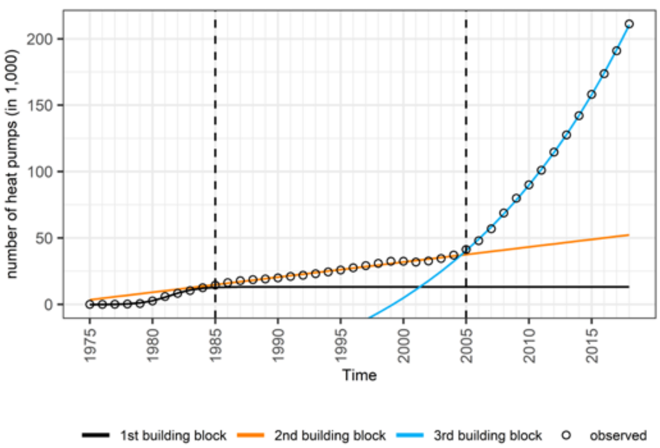
Around the year 2000 photovoltaic gained market visibility and started slow yet with exponential growth. In 2004 PV diffusion shifted to a strong logistic growth. In 2014 the curve changed again to less rapid, but still logistic growth. As of now, the pace of technology diffusion is still fast but levelling off.



*

Heat pumps are the most mature of the four investigated low carbon technologies and entered the market in the early 1980s. Market entry was characterized by a standard logistic function, but in 1985 diffusion changed to a 20-year period of modest linear growth. In 2005, the diffusion curve changed to rapid exponential growth. In comparison to all other technologies, the market diffusion of HP deviates most from the baseline s-shape.

* *Functional parameterization of each building block of the selected best-fit model for each technology: Black, orange and blue lines denote the function of each building block of the selected best-fit model. Black dotted vertical lines denote the year of the change point, where shape of diffusion switches from one building block to the other. Observed empirical market diffusion is illustrated via dots.*

[1] The set of parametric functions of the following growth types, logistic, exponential and linear, before and after each turning point, can be understood as building blocks, which are pieced together to approximate the course of observed technology diffusion over time (see Section C).

Results consumer survey (WP5)

A survey among Austrian homeowners reconstructs how energy efficiency renovations of private residential buildings were preceded by critical events. The study expands on the previous literature by systematically testing the differential impacts of a broad scope of critical events on several renovations, thereby highlighting that critical events do not uniformly apply to all kinds of renovations. Furthermore, the study not only determines whether a critical event brought about a renovation (trigger effect), but also whether this event sparked a faster progression through the stages of implementing the renovation (accelerator effect). The range of critical events investigated includes technical failures, changes in household resources and capacities, changes in the composition of household members, as well as the use of subsidies for the renovation.

Renovations typically take from one to one and a half years, with the planning phase constituting the main share of the overall implementation process (Figure 3). However, variance between households is substantial, suggesting that households draw on a wide range of resources and face different challenges when tackling renovations.

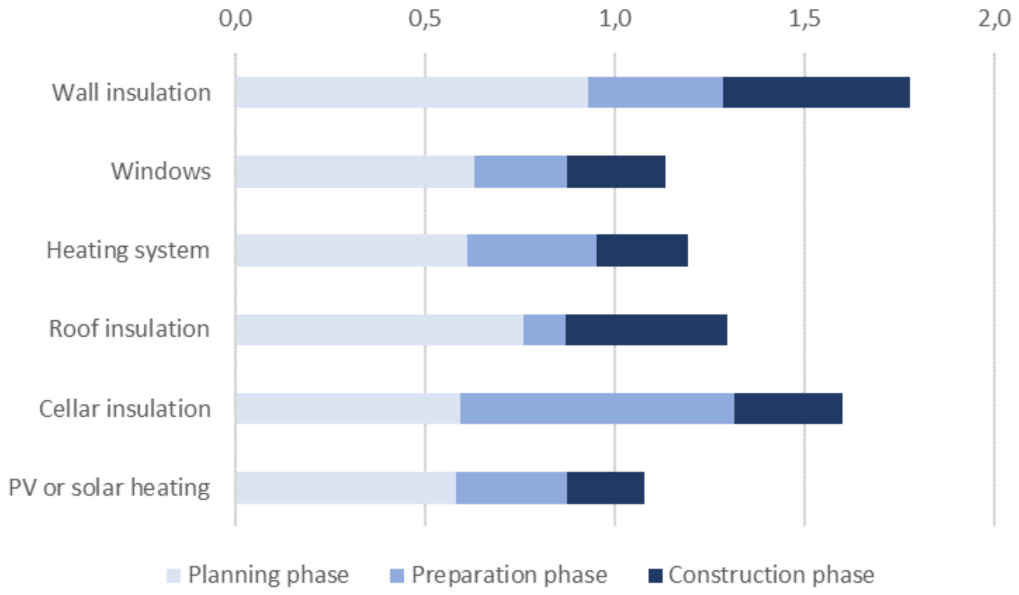


Figure 3 Mean duration of implementation phases in renovation activities.

A trigger effect appears if a renovation becomes more likely if preceded by a critical event. Trigger effects are confirmed only for technical defects of the heating system, roof or windows; these defects instigate a subsequent renovation of this particular building component. By contrast, other critical events show barrier effects (that is to say, negative trigger effects). Technical failures make the occurrence of renovations of other building components less likely; availability of additional household capacities and changes in the family structure similarly inhibit the realization of renovations.

An accelerator effect appears when a renovation is implemented more swiftly if preceded by a critical event. Accelerator effects emerge rarely and apply only when selected technical failures speed up the implementation of other, related building components. Instead, critical events mainly act as decelerators of the planning (the period from considering the renovation for the first time to concluding planning) and preparation (the ensuing stage up to commencement of construction work) phases of the implementation process.

These results underscore the need for a differential perspective, as trigger and accelerator effects do not emerge consistently across different critical events and renovations. This puts into question the common view of critical events as windows of opportunity, when a momentary disruption of everyday routines supposedly facilitates investment choices which would not be taken in the regular course of family life. Such a window seems to open only in regards to replacing a broken building component. In all other instances, critical events apparently preclude or protract the implementation of renovations.

Public subsidies are closely associated with the realization of renovations. While only about a third of renovations applied for and received a subsidy, subsidies substantially increase the probability of a renovation. There is no clear indication that the subsidy paperwork would slow down the implementation process. Subsidies seems fairly effective in supporting renovation; however, for lack of time data the present study could not operationalize subsidies in a strict sense as critical events.

Critical events in the politics, policy and technology stream (WP4)

Based on the chronological timeline of events in each stream and for each technology (see WP2) critical events were determined by means of a stepwise mixed-method approach (see Section on Methodology). A critical event is understood as a (i) focal point in a specific stream that redefined ingrained rules and discourses (e.g. when public mood shifted to favor a particular policy approach or product), (ii) that triggered a chain of subsequent events in the same or other streams (e.g. when a strategy document kicked off a bundle of specific legislation), or (iii) when gradual build-up culminated in a discernible incident (e.g. when engineering progress resulted in the market introduction of a new product family).

General events in the politics stream

Increasingly stringent carbon emission reduction targets directed the politics stream in all three investigated low-carbon technologies towards favoring energy efficiency and renewable energy sources. Therefore, this subsection summarizes the overarching development of Austria's climate policy commitments.

After entering the European Union in 1995 (EC 94/C241/07), Austria joined the Kyoto Protocol in 1998, with the target of reducing carbon emissions by 13% until 2012 (base year 1990), and by 16% until 2020 (base year 2005; UNTC 1998). The protocol "*was the first, critical step towards implementing the energy transition in the real world*" (E3; interviewee codes are referenced in Table A4). In parallel, a 1997 EU action plan stated the objective of increasing renewables in primary energy use from 6% to 12% by 2010 (Scarlat et al. 2015). Consequently, Austria presented in 2002 its first climate strategy comprising emission reduction targets and policy measures for eight economic sectors (Umweltbundesamt 2006). However, around the mid-2000s, Austria came increasingly under pressure to act due to slow implementation of EU directives and little progress in achieving the scheduled targets (Niedertscheider et al. 2018). Consequently, the 2007 revision of the climate strategy committed to stronger efforts, such as enhancing research and development programs and subsidizing investment in low-carbon technologies (Buchegger 2018). In addition, the Austrian Climate and Energy Fund was established (Federal Law Gazette I 40/2007), "*contributing substantially to Austria's sustainable and efficient energy supply and paving the way for the implementation of the national climate strategy*" (E2).

At the same time, the EU presented the climate and energy package, which set a binding emission reduction target of 20% by 2020 (base year 1990). Numerous EU directives ensued in 2008, also addressing electric cars, heat pumps and photovoltaics. In order to comply with these directives, in 2010, Austria passed its Energy Strategy 2020 (BMWFJ 2010) comprising a variety of soft and hard measures. Emission reduction targets were codified in the 2011 Climate Change Act (Federal Law Gazette I 106/2011) which marked "*an important step for Austria towards combatting climate change*" (E7). This act prescribed an overall emission limit; the 2013 amendment added sectoral ceilings for the 2013-2020 period (Federal Law Gazette I 94/2013).

Pursuant to the IPCC's fifth assessment report (IPCC 2013), the EU set in 2014 more stringent emission reduction targets until 2030 – emphasizing renewable energy sources and energy efficiency improvements - and agreed upon a new climate and energy policy framework (Umweltbundesamt 2018, European Council 2014). Accordingly, Austria committed to -36% emissions in non-ETS sectors by 2030 (base year 2005; BMNT 2018). At the COP21 climate conference in Paris 2015, 195 countries, with Austria among them, agreed on limiting global warming to below 2°C (UN 2015). The turnaround moment at the COP21 stimulated continuous public reporting on globalized environmental issues (BMU/UBA 2018, Niedertscheider et al. 2018) and "*increased public awareness towards renewable energy sources and low-carbon technologies*" (E4).

Electric cars

Events in the politics stream

In 1998, the EU reached a voluntary agreement with car manufacturers to reduce vehicle emissions to 140 g CO_2 per km by the year 2008 (Umweltbundesamt 2015; for comparison, average emissions from new passenger cars in 2000 amounted to 167 g). Preempting later EU regulations (see below), China introduced mandatory fuel consumption regulation in 2004 (Zhu and Young 2018) which "*exerted high pressure on European car manufacturers [selling on the Chinese market] and hence made European mandatory fleet emission standards viable*" (Ws). In the end-2000s, two initiatives established a forum for dialogue between policymakers, automotive industry and researchers in Austria: the foundation of the "e-connected" expert network in 2009 (KLIEN 2010) and a large conference on smart e-mobility in 2010 (Städtebund 2010). These initiatives "*led to a momentum in Austria, when policymakers and ministerial officials started taking e-mobility seriously for decarbonizing road transport*" (E1). In consequence, an inter-ministerial coordination task force was established in 2010, which issued a strategic e-mobility implementation plan entailing a range of activities for boosting diffusion of electric vehicles (BMLFUW, BMVIT, BMWFJ 2012). Following up on these developments and in order to transpose the EU alternative fuels directive 94/2014 into national law, the Austrian government published a national strategic framework for clean and low-emission transport in 2016 (BMLFUW, BMVIT, BMWFJ 2016). This document is considered a milestone by many experts since it "*refers explicitly to e-mobility as central element in Austria's future integrated transport system*" (E3).

Events in the policy stream

From 1996 onwards various Austrian provinces subsidized the acquisition of e-cars by up to 15% of the purchase price (Glöckel 1997). In practice, these subsidies were rather symbolic, since at that time e-vehicles were not competitive to conventional cars (e.g. 50% higher purchase price, lack of charging infrastructure). In 2005, the Kyoto protocol went into force and triggered important directives and legislations in the upcoming years. In 2007, the European Commission proposed emission standards for new passenger cars (COM 856/2007). Shortly after, a 2015 target of 130 g CO_2 per km for new passenger cars was passed (EC 443/2009). "*This release was a milestone for e-car diffusion in Austria, because manufacturers were incentivized to sell a sufficient number of these vehicles every year*" (E2), as e-cars were balanced against carbon-intensive cars in a manufacturer's fleet.

In 2008, encouraged by stringent EU car emission standards, the Austrian government initiated the funding scheme "e-mobility region" to support market diffusion of e-cars (KLIEN 2016). From 2008 to 2015, seven e-mobility regions with a total budget of 16.2 million EUR were established (AustriaTech 2016). "Vlotte" the first e-mobility region located in the province of Vorarlberg, obtained with 5.2 million EUR by far the highest budget of all these regions, and "*is considered a milestone in introducing e-mobility to a broader public, due to numerous communication activities and the construction of charging infrastructure*" (E1). The seven e-mobility regions purchased 1,500 e-cars between 2008 and 2015 for sharing and testing, which amounted to 40% of the total number of e-cars in Austria (KLIEN 2016). EU emission standards for new passenger cars were tightened in 2014 to 95 g CO_2 per km by 2021 (EC 333/2014). Although e-cars started to enter the market in 2011, emissions from passenger transport continued to increase in the EU and Austria (UBA 2016, EEA 2019). Therefore, a 2014 EU directive called for alternative fuels in transport (EC 94/2014).

Also as a reaction to EU car emission standards, Austria issued tax privileges for e-cars. From 2014 onwards, the basis of the vehicle acquisition tax referred to carbon emissions, hence favoring vehicles with alternative fuels. As part of the Austrian tax reform 2015/16, e-vehicle purchases were exempt from VAT tax for enterprises and electric company cars qualified for free private use (Federal Law Gazette I 118/2015). These measures "*presumably achieved the increase in private e-car ownership to 1.5% in 2015, and made Austria the number-one country in terms of per capita e-vehicles in the EU28 in 2016*" (E3).

Events in the technology stream

In 2008, the Tesla Roadster was introduced to the US automobile market (Spiegel 2011). It was the first electric vehicle with a range of over 350 km and a speed of over 200 km/h (Pfaffenbichler et al. 2009). Although the Tesla Roadster was exported to Europe as late as 2009 and only 250 units were available, "*it paved the way for mainstream acceptance of e-cars*" (E2). Incremental progress in materials, battery lifetime and range, and car body design led to decreasing acquisition costs (e.g. battery costs fell by 14% annually between 2007 and 2014; Nykvist and Nilsson 2015) and higher reliability of e-cars (Vynakov et al. 2016, Gnann et al. 2018). In 2010 serial production of the Mitsubishi iMiEV started and in 2012 the Nissan Leaf came on the Austrian market (Koarik 2011). The Nissan Leaf was the first everyday e-car, at acquisition costs competitive with fossil-fuel powered vehicles (Klose 2019). "*The availability of a wide e-car product range, in particular for daily use, at more and more compatible costs is a direct result of the mandatory fleet emission limits*" (E1). Additionally, 2012 marks the year with the historically highest gasoline prices (Keichel and Schwedes 2013), making e-cars attractive because of low fuel costs.

Heat pumps

Events in the politics stream

In the aftermath of the first oil crisis in 1973, the Austrian government released its first energy strategy in 1976. Influenced by Austria's broad anti-nuclear movement in the mid-1970s, this strategy highlighted alternative energy sources, in particular heat pumps, in order to reduce import dependency and increase energy efficiency (Energieplan 1976). An Austrian task force quantified exploitability and costs of heat pumps in private buildings (Energiebericht 1979), drawing on energy scenarios which estimated heat pumps to provide half of future residential heating (Gilli et al. 1978). The second oil crisis in 1979 further encouraged these ambitions and led to rapid market uptake in 1980. However, starting in the mid-1980s, "*other alternative, renewable heating systems, in particular biomass heating, became more prominent on the political agenda*" (Ws).

As a reaction to technological shortcomings and degrading public opinion on heat pumps (see technology stream below), the quality label DACH was established in 1998 in cooperation with Switzerland and Germany (Kiss et al. 2011). This initiative of heat pump producers and installers aimed to ensure product quality by guaranteeing minimum efficiency values, customer service and a two-year warranty. In the mid-2000s, the DACH label was gradually improved by ratcheting up product requirements and expanding the number of member states; in 2009 it was replaced by the EHPA Quality Label (EHPA 2009). Still, skepticism on the technical reliability and environmental benefits of heat pumps persists to the present day: "*It seems that heat pumps, although the most efficient technology, are still not perceived as a green technology because they run on electricity*" (E7).

Events in the policy stream

Implementing the 1976 energy strategy resulted in a subsidy program for heat pumps in private buildings (Federal Law Gazette 337/1978), and a funding program for research and development on heat pumps. The R&D program was an international collaboration, where Austria participated with a budget of 150,000 USD, triple as much as Germany and Switzerland (Federal Law Gazette 214/1980). These activities supported heat pump diffusion in the early 1980s, but trickled away in absence of follow-up measures. Since the early 1990s, selected Austrian provinces subsidized heat pumps for new residential buildings. However, "*due to the complex provincial funding system in Austria, there is no reliable information on the magnitude and impact of provincial funding schemes*" (E8).

After Austria's EU accession in 1995, the transposition of EU directives into national law created a more supportive policy environment for heat pumps. Aligning mineral oil tax with EU standards raised tax rates for heating oil by 50% to 150% (Federal Law Gazette I 297/1995). However, crucial impetus evolved from the gradual tightening of building standards. Austria had regulated minimum energy efficiency requirements for new buildings as early as 1995 (Federal Law Gazette 388/1995). The EU energy performance of buildings directive in 2002 (2002/91/EC) marked the beginning of a period of consecutively stricter standards. "*The EU directive introduced the energy performance certificate, obligatory when constructing, selling or renting residential space, which supported the deployment of energy-efficient heating technologies*" (E9). In 2006, all nine Austrian provinces agreed on a harmonized set of energy efficiency requirements for housing subsidies, which was a remarkable achievement in a federal governance structure such as Austria (Federal Law Gazette II 19/2006). On behalf of the national government, the Austrian Institute of Construction Engineering released binding rules that apply uniformly across Austria. "*These guidelines stipulated maximum heating demand and energy-efficient construction. They were an important milestone towards accelerated diffusion of heat pumps*" (E9). In 2010, a revision of the EU buildings directive set more stringent energy performance standards, requiring by 2021 that all new constructions are near-zero-energy buildings (2010/31/EC). The Austrian building ruleset was adapted stepwise to ensure that new buildings met the EU zero-emission target in 2020. "*The building standards were groundbreaking, since heat pumps were recommended as technology capable of fulfilling the strict heating demand requirements*" (E8).

Additional promotion of heat pump diffusion resulted from subsidies for building renovation. Originally in response to the 2008 global economic crisis, but then to comply with emission reduction targets in the housing sector, the Austrian government funded thermal retrofitting and switching to renewable heating with 60-70 million EUR per year in the 2009-2014 period (BMNT 2017); this subsidy program is still ongoing.

Events in the technology stream

As the oil price returned in the mid-1980s to the lower pre-crisis level, heat pumps lost their cost advantage over fossil-fuel heating systems (Kiss et al. 2012). Early mass production struggled with quality issues and consequently "*the originally positive public opinion on heat pumps declined sharply*" (E7; Faninger 2007). In numerous European countries, heat pump sales dropped massively, and the global market collapsed in 1985 (Nyporb and Ropke 2019). However, starting in the 1990s, heat pump technology continuously improved. Geothermal heat pumps gained enough significance to be recorded in market statistics by 1989 (Faninger 2007). Between the 1980s and 2010s, acquisition costs more than halved due to economies of scale (Kiss et al. 2012), which "*was one the most important events for the diffusion of heat pumps*" (Ws). Moreover, the coefficient of performance of heat pumps (COP, i.e. the ratio of heat provided to electric power required for operation) improved by 15-30% from the early 1990s to the early 2000s (WPZ 2001, SVEP 2007). By the late 2000s, heat pumps had become a highly efficient heating technology (e.g. a COP of 2.4 in air-to-air heat pumps compared to 0.9 in oil heating; Ducoterra 2014). These technological improvements traced back to the DACH quality label (see politics stream). The 2006 standards (see policy stream) for energy performance of buildings "*favored heat pumps in terms of costs and performance*" (E8), thereby pushing market development.

Photovoltaics

Events in the politics stream

Since the 1997 EU action plan, European as well as Austrian climate and energy strategies featured PV as a core element for complying with the Kyoto, EU2020 and Paris Agreement carbon emission reduction targets (see Section 4.1). In 2000, the German Renewable Energy Sources Act went into force (Federal Law Gazette 13/2000), setting a frontrunner example in energy policy by providing unlimited feed-in tariffs for PV-produced electricity over a 20-year term. The German initiative spilled over to Austria as "*extensive media coverage improved public opinion on PV as green and self-generated energy source*" (Ws) and *"PV panel prices dropped from high German demand, which also activated the Austrian market*" (Ws). A decade later, the nuclear disaster in Fukushima 2011 *"returned PV to the center of the public debate and triggered a number of policy adaptations on the EU and national level*" (E4).

Events in the policy stream

The "200 kW Breitentest" project in 1992 constitutes the beginning of targeted policy action for PV diffusion in Austria (BMVIT 2002). While limited in funding scope and installed PV capacity, the project demonstrated the practical feasibility of small-scale installations (Kapusta et al. 2002). In the 2000s, policy actions gained momentum on the EU and national level. In 1999, the Austrian Electricity

Industry and Organization Act (Federal Law Gazette I 1998/143) went into force, transposing the EU electricity market directive (96/92/EC) into national law. *"The liberalization of the Austrian electricity market opened the market to new actors and builds hence the foundation for future legislations"* (E6). Subsequently, based on the 1997 EU action plan, an EU directive (2001/77/EC) tasked member states with promoting electricity produced from renewable energy sources, such as PV. Austria took action in 2002 by passing the Green Electricity Act (Federal Law Gazette I No 146/2002), inspired by the German role model legislation; this act established feed-in tariffs and mandated energy utilities to purchase electricity from renewables. The act made way for *"a uniform nation-wide support scheme for green power*" (Ws). However, in 2004, PV diffusion halted abruptly, because the act had foreseen a 15 MW cap on PV installations eligible for feed-in tariffs, and this cap was reached already in 2003 (Biermayr et al. 2018).

The mid-2000s brought revisions in PV funding and policy support. An amendment to the Green Electricity Act in 2006 created a designated accounting center, the "OeMAG Abwicklungsstelle für Ökostrom", which distributes feed-in proceeds to PV operators. In 2008, the recently established Climate and Energy Fund launched a grant program subsidizing investment costs for small-scale PV systems with <5 kWp capacity (KLIEN 2008). The initial program budget of 8 million EUR was significantly increased each succeeding year (2009: 18 million EUR; 2010: 35 million EUR) to satisfy the unexpectedly high demand. In return, the 2008 amendment of the Green Electricity Act abandoned feed-in tariffs for <5 kWp PV systems (Federal Law Gazette 114/2008). The piecemeal amendment of support schemes in the mid-2000s *"created uncertainties regarding planning and financing among private and commercial operators*" (Ws) and is supposed to have cushioned market diffusion.

The 2012 reissue of the Green Electricity Act (Federal Law Gazette I 149/2002) transposed the EU renewable energies directive (2009/28/EC) into national law. The reissue allocated a one-off extra budget of 28 million EUR for reducing the high backlog of applicants for investment subsidies. In 2013, 263 MWp of PV capacity were newly installed in Austria, thus marking the point in time where the 1% threshold of domestic electricity consumption was exceeded (PVA 2019). *"This surge is strongly related to the extra 28 million EUR budget*" (Ws). As of now, the investment subsidy program for small-scale PV systems is still ongoing; in hindsight, the program helped to "*build a well-established domestic market*" (E2). The subsidy rate was scaled down from 2,800 EUR per kW in 2008 to 275 EUR per kW in 2015 to counterbalance the decline in PV panel costs over the same period from > 6,000 to < 2,000 EUR per kW (KLIEN 2016).

Events in the technology stream

PV technology was already well advanced in the early 1980s; over the 1990-1999 period, installation costs of PV systems in Austria more than halved, likely as a result of the "200 kW Breitentest" project (Kapusta et al. 2002). As European demand for PV panels surged in the early 2000s, China expanded production capacity significantly and became world leader in solar cell manufacturing in 2008

(Zhang et al. 2013). Since 2009, considerable overcapacities incurred fierce competition in the PV panel industry, which, in turn, cut world-market prices considerably (Fraundorfer ISE 2018). For instance, PV module prices dropped by 58.5% from 2011 to 2015 (Theo and Liebl 2016). In 2013, the EU imposed an anti-dumping duty of 0.56 EUR per Wp on Chinese PV panels to protect the European industry (1238/2013/EU). Price increases from this duty "*might have restrained cumulative installed capacity"* post-2014 (Ws).

Explaining turning points in market diffusion of low-carbon technologies (WP6)

Finally, in an integrated manner the results of WP4 and WP5 were brought together in order to explain the occurrence of turning points by means of the underlying compact selection of critical events.

Explaining turning points in market diffusion of electric cars

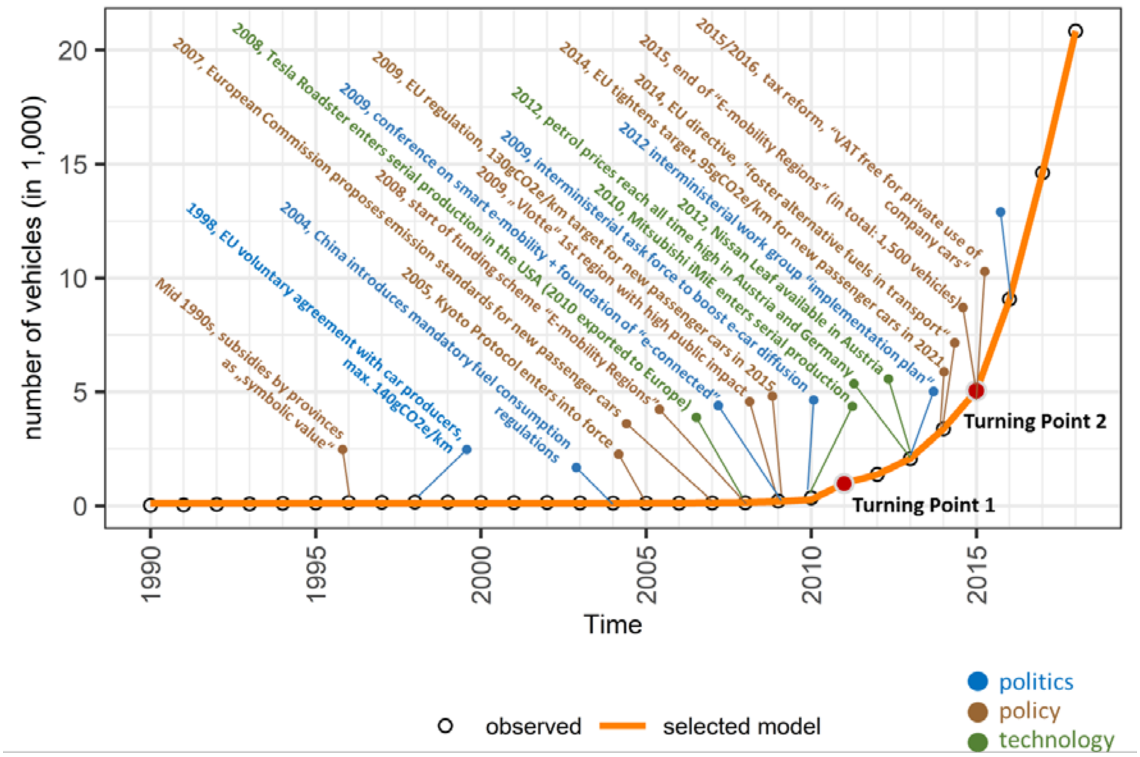


Figure 4. Market diffusion curve with turning points and critical events in the politics, policy and technology streams for electric cars

Explaining Turning Points: Increasingly strict EU car emission standards from 2009 onwards provided the impulse for national schemes promoting e-cars and the construction of charging infrastructure. The 2011 turning point seems to be the direct consequence of this generous funding, as the hump in the 2010-2012 diffusion period may reflect how the large-scale acquisitions of e-mobility regions temporarily boosted exponential market uptake. When the e-mobility regions program was discontinued in 2015, this pull-forward effect diminished and market development fell back to its original logistic growth. After the second turning point, car manufacturers had extended their product range following the Tesla role model and had reacted to the policy pressure of EU fleet emission restrictions. Additionally, Austrian had implemented tax deductions that made e-cars attractive for small, privately owned enterprises.

Explaining turning points in market diffusion of heat pumps

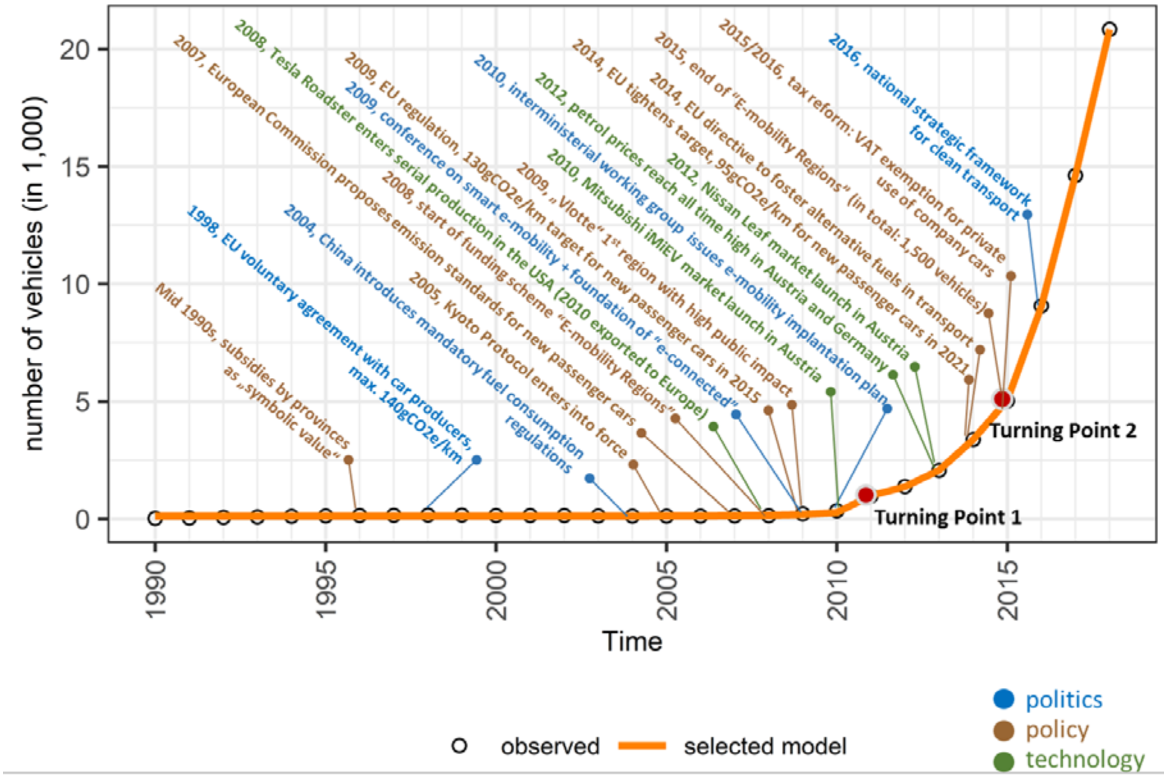


Figure 5: Market diffusion curve with turning points and critical events in the politics, policy and technology streams for heat pumps

Explaining Turning Points: Early dynamic market uptake up to the first turning point in 1985 traces back to the aftereffects of the 1973 and 1979 oil crises, as heat pumps offered cost advantage and independency from fossil-fuel imports. Governmental R&D programs and acquisition subsidies played a complementary role during this stage. However, this promising development turned to a 20-year lean spell of slow diffusion, as impeding factors piled up in all streams: return to low oil prices and higher interest in other renewable energy sources in the politics stream; a lack of follow-up measures in the policy stream; and product quality issues in the technology stream. The second turning point in 2005 indicates how these impeding factors were resolved by introducing energy standards for buildings, subsidizing the switch to renewable heating, and advancing heat pump technology by quality labels, higher efficiency and lower acquisition costs.

Explaining turning points in market diffusion of photovoltaics

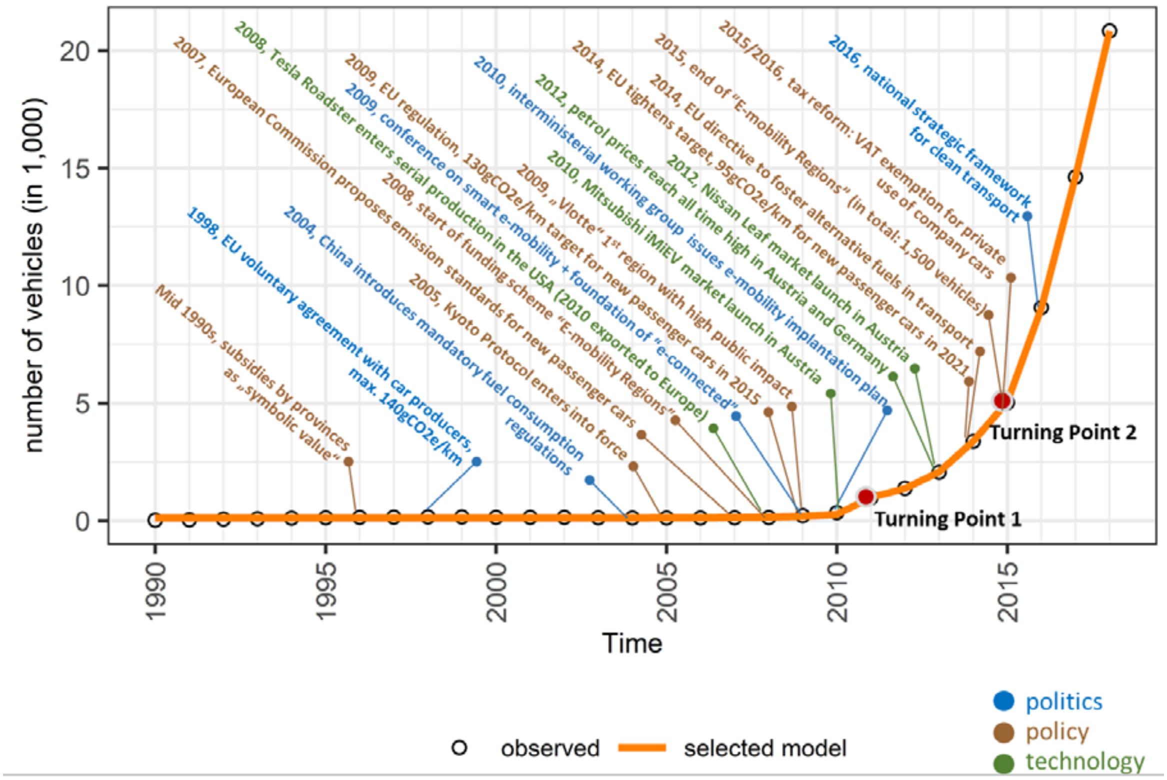


Figure 6: Market diffusion curve with turning points and critical events in the politics, policy and technology streams for photovoltaics

Explaining Turning Points: The first turning point in 2004, when exponential growth transitioned to logistic growth, most likely indicates how the 15 MW cap on feed-in tariffs in the initial Austrian Green Electricity Act choked off demand. Over the next decade, favorable public mood, a patchwork of support schemes and decreasing PV panel prices coincided for dynamic growth. Subsidy budgets had lagged behind demand for several years; the second turning point in 2014 marks the moment in time when PV installations peaked because of one-off extra funding, but also when subsidy grants were downscaled in the light of decreasing world-market prices for PV panels. The sequential logistic functions before and after the second turning point may indicate different levels of market saturation: Extrapolating the logistic function of the 2004-2014 period suggests that the market for PV installations reliant on investment and feed-in support would have been saturated shortly after 2020. By contrast, extrapolating the post-2014 logistic function lets expect a more hesitant, but much higher market potential of PV installations mainly driven by panel prices.

5 Conclusions and recommendations

Comparison of accelerators and decelerators of market diffusion of the studied technologies

The results do not confirm the s-shaped baseline model of market diffusion for any of the analyzed three low-carbon technologies. Instead, the alternative models suggest more complex growth curves that shift in function (logistic, exponential or linear) and parameterization (accelerating or decelerating) at specific turning points. Apparently, real-world diffusion processes reorient in direction and pace at specific moments in time. This conforms with our critique of an uniform s-shape as an idealized and oversimplifying conceptualization of market diffusion.

In line with the Multiple Streams Approach, turning points are observed once supportive impulses in the politics, policy as well as technology stream converge. Climate targets provide an overarching incentive for action. However, as exemplified by the e-cars and heat pumps cases, these overarching politics need to be translated into mandatory standards which then either trigger technological advancement, as car manufacturers were forced to add electric compact cars to their product portfolio, or facilitate access of an already viable technology to the mass market, as re-engineered heat pumps could bring their now high performance and reliability to bear.

Besides the apparent leverage of mandatory standards, effective policy impacts on market diffusion may arise from R&D programs and product quality labels which assist during early-stage technological progress, as in the case of heat pumps during the 1980s to 2000s. Neighboring countries and global influences play a complementary role, as underscored by the positive spillover of German renewable energy legislation on Austria’s PV funding schemes, the international DACH label ensuring heat pump quality and Chinese fuel consumption standards enabling mandatory fleet standards in Europe. Coordinative bodies between governmental sectors or between market actors may facilitate effective policy deployment. The examples of the inter-ministerial e-car task force or the OeMAG PV feed-in tariff administrator highlight how bundling of expertise and competences steers concerted action for speeding up market diffusion.

By contrast, unspecific subsidy programs appear to be less effective for advancing diffusion of low-carbon technologies. The diffusion impact of Austrian subsidy programs seems constrained to pull-forward effects, as in the temporary sales boost from the e-mobility regions scheme, or to fueling adoption in a restricted customer segment, as the photovoltaics segment responsive to feed-in tariffs and investment grants might have been saturated within a few years. The Austrian photovoltaics case furthermore gives a counter-example of disjoint streams: During the 2000s, customer uncertainty accumulated from the combination of patchwork policies, as subsidy amounts and eligibility were adapted every few years due to continuous amendments of the green electricity act, and volatile world-market price formation. Consequently, diffusion pace slowed after the second turning point in 2014.

Finally, our results do not suggest that the investment cycle of a technology influences the relation between turning points and critical events. For instance, heating systems typically have a service life of thirty years, whereas car turnover may take less than a decade. Shorter investment cycles would imply that critical events take hold more directly; yet, heat pumps as well as e-cars both featured periods of fast and slow market growth. However, it remains an open question whether this observation also applies to other low-carbon technologies than those investigated here.

Recommendations for climate policy

The need for rapid decarbonization of the energy system calls, notwithstanding other actions, for accelerated market diffusion of low-carbon technologies. Market take-off typically occurs when politics, policy and technology streams converge. This project demonstrates a methodology for determining constellations when and why a turning point occurred by i) mathematically identifying shifts in market diffusion and ii) reconstructing critical events in past socio-political developments preceding the shifts identified in i). Applying this methodology to the cases of electric cars, heat pumps and photovoltaics in Austria illustrates entry points for targeted policy action to promote energy-efficient, low-carbon technologies.

Based on our findings we conclude that effective policy interventions for promoting low-carbon technologies at the national level require certain prerequisites: First, binding targets and regulatory stipulations are key levers, but need to be accompanied by actions in the politics, policy and technology stream. This conforms with recent findings (e.g. Steurer 2013). Second, continuously monitoring all streams may allow to detect barriers impeding market diffusion or to anticipate potential upcoming turning points. Targeted action resolving barriers or aligning streams could trigger rapid growth or shift logistic growth dynamics to a higher saturation point. Third, tailor-made policy interventions require reflexive and adaptive policy integration; both horizontally and vertically (Nilsson and Weitz 2019, Kurze and Lenschow 2018). This calls for continuous coordination across economic sectors, policy spheres and technologies. In general, transitioning to a low-carbon society should not be mistaken for pushing the maximum market penetration of a favorite technology. Instead, policy mixes should seek an optimal interplay of complementary technologies which jointly contribute to carbon emission reduction or even sustainability targets.

Change point analysis offers an empirical technique for determining the point in time when turning points take place; the parameterization of functions provides estimates of diffusion pace and expected level of market saturation. The quantitative estimates of change point analysis expand on qualitative expert assessments of diffusion dynamics that are at risk of bias from vested interests and research paradigms. Still, for explaining why turning points take place, expert judgments remain essential to capture politics discourses which are often informal, sporadic and sparsely documented. Moreover, change point analysis enables to project future diffusion dynamics and may provide a useful planning tool for strategic policy.

However, change point analysis underlies inherent methodological limitations, as model estimates critically depend on the number of data points available from market statistics. When using short time series, or when examining the early stage of transitioning from niche product to market mainstream, extending the time series by additional data points could shift turning points or yield different parameters. By contrast, model estimates presumably are robust if a technology has been established on the market for some time or already entered the saturation stage. We thus recommend sensitivity analyses by restricting or widening the range of data points analyzed. Model estimates should be re-checked every few years as recent market statistics become available, in particular if unexpected political or technological breakthroughs occur. We also caution against interpreting turning points as exact moments of historical change; turning points rather mark periods of reorientation. Explaining turning points in hindsight may be colored by an over-deterministic perspective that overrates causal relations between critical events and diffusion outcomes. By applying a mixed-method approach in identifying critical events, we strived to reduce this uncertainty.

While the present study focuses on selected low-carbon technologies in Austria, we would welcome replication in other countries and to other low-carbon technologies. For example, heat pumps are projected to reach market saturation in Norway by 2030 (Sartori et al 2009, Heimdal 2011), which might offer an interesting case for a long-term analysis spanning all diffusion stages. Further research potential lies in interrelations between technologies: For instance, electricity produced by photovoltaics panels on private roofs could charge a local e-car or operate a heat pump instead of being fed into the grid. This interrelation would suggest a joint technology stream for control systems and grid integration. A joint policy stream could address subsidy schemes or building standards with a multi-technology scope. As a negative example from Austria, providing photovoltaics investment subsidies for private households only up to 5 kWp counteracts cost-efficient self-consumption of the produced electricity since e-cars or heat pumps typically require higher power output. As a positive example, the 2015 revision of the Viennese building code prescribes empty cabling conduits in new underground garages in order to enable later retrofitting of e-car charging stations (Provincial Law Gazette No 96/2018). Decarbonizing the energy system may necessitate a multi-technology perspective; future studies could analyze how the diffusion processes of interrelated technologies co-evolve and how their joint market development feeds back to the general politics stream.

Finally, decarbonizing the energy system is not only about promoting innovative technologies, but also about phasing out fossil fuel-based technologies. Heat pumps gained traction in Austria as soon as strict standards favored the installation of alternative heating systems over oil heating in new buildings; recent policy strategies foresee a dismantling of oil heating in existing buildings from 2025 onwards. EU car emission standards simultaneously pushed e-car market entry and narrowed the market position of gasoline-powered cars. Future research could apply the turning point methodology not just to growth, but also to de-growth processes. This calls not only for theoretical assumptions on the shape of a phase-out baseline curve to be tested but also the interrelation of both, phase-out of the conventional technology and phase-in of the innovative technology, in a multi-model framework.

C) Project details

6 Methodology and concepts

We integrate Diffusion of Innovations Theory (Rogers 1983) with the Multiple Streams Approach (Kingdon 1984) by their constitutive element of turning points. We do so in three steps (Figure 7 provides an overview of the integrated approach): First, the mathematical technique of change point analysis compares historical market data to the baseline s-shape to determine the calendar years when turning points in market diffusion occurred. Second, document analysis and deliberation with experts reconstruct socio-political developments related to market diffusion as a sequence of critical events in the politics, policy and technology stream. Third, these sequences of events are integrated into storylines to explain in hindsight how turning points emerged from continuous buildup or critical junctures between the three streams. Thereby, on the one hand, we advance the discussion on dynamic and pace of technology diffusion, which is particularly important for advanced scenario analysis and forecast models (van der Kam et al. 2018, Harris et al. 2018); on the other hand, we demonstrate a systematic methodology for understanding past developments in order to inform future diffusion efforts.

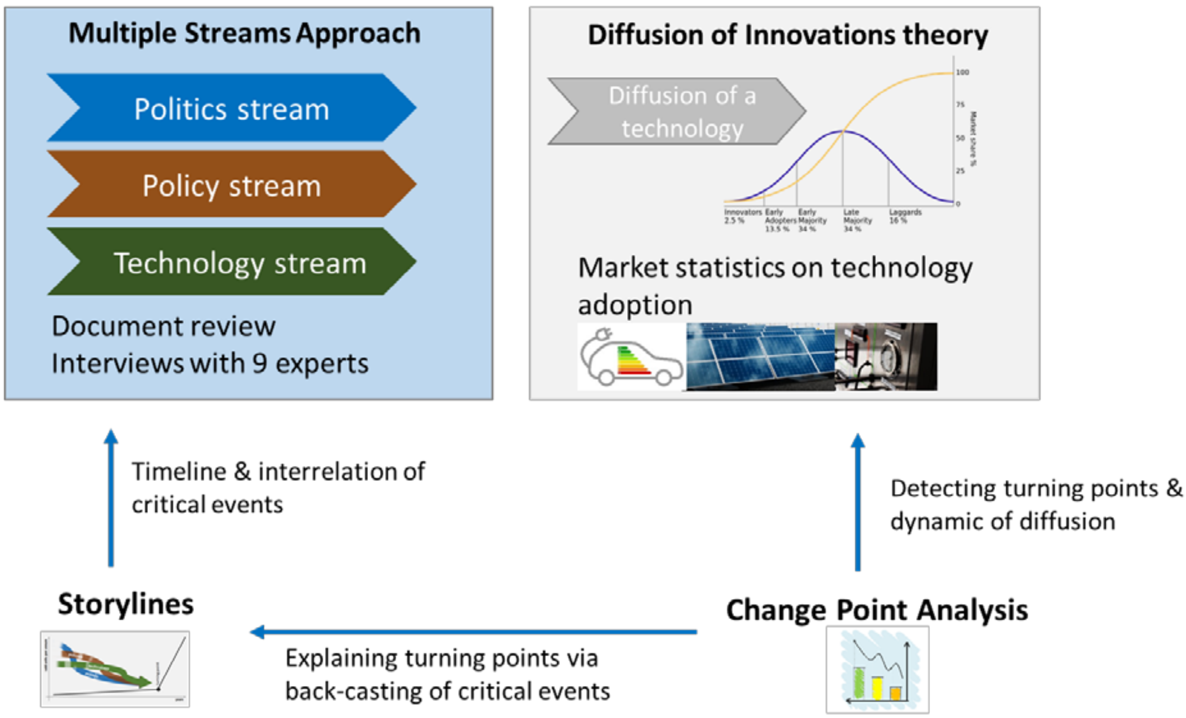


Figure 7 Overview of the mixed method approach employed in TIMELAG

Multiple Streams Approach

The Multiple Streams Approach (MSA; Kingdon 1984) posits that policy change (window of opportunity) arises if three independent streams coincide: the Politics stream as shifts in public opinion, the policy stream as the sequence of formal decisions and legislation, and the problem stream as an issue of concern that draws the attention of policymakers and the public.

We use Kingdon’s theory as a heuristic to explain the market diffusion of low carbon technologies via three streams (i) *politics*, (ii) *policy* and (iii) *technology*. While the first two streams replicate Kingdon (1984), we abstract from the problem stream and draw on the technology stream instead (details are reported in Table 3). The latter one is of particular relevance for the studied low carbon technologies, where the stage of development is a key determinant. Numerous studies (Lee et al. 2012, van der Kam et al 2018, Simpson and Clifton 2016) identify technological aspects, such as investment costs, operating costs, reliability and level of comfort, as key drivers of innovation. Similarly, from the viewpoint of transition theory, Cherp et al. (2012) argue, based on their meta-theoretical framework, that only the coevolution of techno-economic systems (i.e. market conditions, physical energy flows), socio-technical systems (i.e. technical change, infrastructure, technical artefacts and attributes) and political actions (i.e. change in policies, political parties, social movements) steer a successful transition. Note that regarding the policy and politics stream the multilevel governance structure (federal, national and EU level) is particularly relevant and specially emphasized. Furthermore, regarding the technology stream, various factors are discussed as well as analyzed in relation to the competing dominant fossil based technology (e.g. purchaser costs of electric vehicles compared to standard gasoline vehicles).

Table 3. Definition of streams

Stream	**Definition in energy and climate research***	**Definition in the present study**
Politics	Perception of public opinion, national mood, election results, ideologies and opinions of policy makers and people in charge	Social discourse, public awareness, activities of lobbyists and interest groups, media presence, new institutional structures such as formation of a working group or grant fund dedicated to the technology, global policy developments, non-binding policy strategy documents, overall emission reduction targets (e.g. Kyoto 1997, EU2020)
Policy	Passing of legislation, implementation of specific policy instruments, ratification of international multilateral agreements, advancement of ideas and strategies	Availability of subsidies, passing of taxes or regulations specifically targeting the technology, technology-specific R&D programs, assigned within the multi-level governance structure of federal, national and EU bodies
Technology	Included as problem stream: perception and urgency of a contested issue requiring a solution	Technology readiness level, purchase price and operating costs, spectrum of products available on the market, reliability, comfort, duration of life, technological leaps, uncertainty over costs and technological development

**: Brunner 2008, Boswell and Rodrigues 2016, Grossmann 2015*

Applications in the field of climate change and technology transition are manifold. Brunner (2008) explains by means of MSA Germany’s sudden policy change to auctioning in the EU ETS implementation phase (Brunner 2008). MSA has been applied to explain the evolution of the 2008 Climate Change Act in the UK, a radical and ambitious piece of legislation (Lorenzoni and Benson 2016, Carter and Jacobs 2013). Other applications in this context comprise the emergence of policy windows in energy policy (Grossmann 2015), evolution of environmental innovation policies in Germany (Nill 2002), origins of the Zero Emission Vehicle rule in California (Collantes and Sperling 2008) and the role of material efficiency solutions in policies to reduce GHG emissions from cars in the UK (Cooper-Searle et al. 2018).

Commonly MSA streams are dimensionless and evolve next to each other independently over time. We advance this illustration by showing how events and developments increased over time in each stream and start to culminate over time. If the culmination process proceeds in all streams, opportunities open up and turning points happen. In other words, a stream reaches a certain readiness level. This idea that different processes and streams have to culminate and be ready is not new in technology transition and forecasting. Kobos et al. (2018) argue that in addition to technology readiness, adequate market conditions and regulatory requirements have to be established in order to enhance diffusion speed and adoption of technologies (leading to radical change). Similarly, we argue that turning points occur if events in the three streams build up and culminate. In cases where only two streams advanced sufficiently, substantial changes in the diffusion curve do not happen. For example, if the technology is developed far enough and policy measures supporting market uptake are in place, but national mood is not in favor of this development, market diffusion is hindered.

Diffusion of Innovation theory

Rogers (1983) describes the adoption of innovative technologies as a s-shaped, i.e. logistic, curve: Initial slow development attracts only innovators and early adopters, followed by rapid upscaling to the early and late majority of consumers, until a plateau of market saturation is reached when even laggards have eventually adopted the technology. The s-shaped curve is also used in the Bass diffusion model (Bass 1969, Adner 2002) and the Fisher–Pry model (Fisher and Pry 1971, Gnann et al. 2018). The s-shaped curve has been extensively applied in energy and climate research to forecasting innovative technologies, for instance to the cases of photovoltaics and e-car use (Dong et al. 2016, Kurdgelashvili et al. 2019, van der Kam et al. 2018, Guidolin et al. 2010), digital innovation (Michalakelis et al. 2018, Oughton et al. 2018), renewable energy (Devezas et al. 2008, Lee and Huh 2017, Xu et al. 2016), carbon mobility (Björn et al. 2011) and energy generation (Harris et al. 2018). Empirical evidence however, shows that observed diffusion patterns deviate from the idealized s-shape. For instance, Sood and Tellis (2005) identify consecutive s-shapes for several technologies, suggesting several turning points where refreshing and pause phases alternate; they also observe linear instead of exponential growth during the take-off phase.

Still, the s-shaped pattern is widely accepted in the scientific community. Thus, it serves as the null hypothesis and baseline model of the present study. The s-shape features two turning points at the transitions between the three stages of technology diffusion: slow onset, rapid growth and saturation. The methodological step of change point analysis tests a range of alternative models that represent these three stages as sequences of exponential, linear and logistic functions, with the aim of providing a more realistic and accurate picture of real-world market dynamics.

Change Point Analysis

The mathematical technique of change point analysis estimates when the empirically observed technology diffusion curve changes pace and shape, and turning points occur. A stepwise methodological approach is adopted to compare the observed market diffusion of low carbon technologies to Rogers' s-shape pattern; first to show when (turning points), second to show how (parametric functions) the observed diffusion curve deviates from the baseline s-shape. Different alternative models, consisting of a variety of functions and number of turning points, were compared to an s-shaped baseline model. For reasons of brevity, full mathematical information on model specification and estimations can be found in Kulmer et al. (in press).

Step 1: Baseline model

By means of case studies, Roger (1983) found that the adoption of an innovation over time follows a bell shaped normal distribution and consequently the cumulative number of units adopted shows an s-shaped curve of diffusion. The s-shaped diffusion curve provides the null hypothesis of this study, reflecting the theoretically assumed baseline model of technology diffusion. Mathematically speaking, the s- curve corresponds to a logistic function (see Table 4). As at the starting year of our time series data, a small number of units had already been adopted, the observed technology diffusion curve does not originate at zero.

Step 2: Alternative turning point models

Three alternative models with one or two turning points are fitted to the observed technology diffusion data: (i) Smooth TP: Model with one or two turning points, where after each turning point a new parametric function may follow and with the condition that the whole function is smooth. (ii) Discrete TP: Model with one or two turning points, where after each turning point a new parametric function may follow. In contrast to above, this specification allows for discrete functions in order to cater to fluctuations and volatility in real-world market environments. (iii) Two TPs: Model with two turning points, with the same parametric function applied before the first turning point and after the second turning point, and another parametric function between the two turning points. This specific model allows detecting pull-forward effects, a special case of market dynamics. One prominent example is the German accelerated vehicle retirement program, which led to a sharp increase in demand for new cars as long as the policy was active, but shortly after the policy was discontinued, the car registration numbers returned to the pre-policy trend (Böckers et al. 2012).

Each alternative model consists of a set of parametric functions before and after each turning point, where each function reflects one of the following growth types: logistic (identical to the Baseline model), exponential and linear (see Table 4). These growth functions can be understood as building blocks, which are pieced together to approximate the course of observed technology diffusion over time. Due to the number of parameters to be estimated and the short time span of available data, the number of turning points is restricted to maximal two. Otherwise, overfitting would be an issue.

Table 4. Specification of the growth functions

Type	Functional form*	Description
Logistic	$F = \frac{C}{1 + \exp\left(-(a + bt)\right)} + D$	b denotes the logistic growth rate and controls the slope of the curve, i.e. the pace of technology diffusion. The term $-\frac{a}{b}$ is the midpoint of the logistic curve, i.e. the point in time when the annual growth rate levels off. C denotes the maximal, satiated value of the logistic function, while D is the minimal, starting value of the curve.
Linear	$F = a + bt$	b is a linear growth factor and a denotes the intercept. If we approximate the logistic function (with parameters a_l, b_l, C_l, D_l) near a point t_0 with a linear function then we would estimate the parameters as follows $b = b_l * C_l \frac{e^{-(a_l + b_l t_0)}}{1+e^{-(a_l+b_l t_0)}}$ and $a = \frac{C_l}{1+e^{-(a_l+b_l t_0)}} + D_l - t_0 * b$.
Exponential	$F = e^{a+bt} + D$	D denotes the intercept starting level of the curve, while b describes the exponential growth rate. Note that in case of small values of t, the growth rate corresponds to logistic growth. The term e^{a} is a multiplicative factor. If we approximate the logistic function (with parameters a_l, b_l, C_l, D_l) near a point t_0, we would estimate the parameters as follows $b = b_l, D = D_l$ and $a = \log(C_l e^{a_l}) - \log(1 + e^{a_l + b_l t_0})$.

*In all cases, F describes the technology diffusion in year t.

Step 3: Parameter estimation for each alternative model variation

Every possible combination of number of turning points and type of growth function in the alternative models is estimated. The advantage of this additive approach lies in its ability to detect the point in time when the shape of the diffusion curve changes as well as to identify how the curve changes in terms of dynamic and pace (e.g. exponential or linear acceleration in diffusion). The drawback however, is the large number of variations of functions to be estimated. For each alternative model, 33 variations are possible from all permutations of three growth functions and one or two turning points: 3^2 variations of one turning point models plus 3^3 variations of two turning point models. Consequently, model selection is crucial.

Step 4: Model selection

The model selection relies on the corrected Akaike Information Criterion (AICc) (Akaike 1973) which is a second order correction for the approximation of the Kullback-Leibler distance between the distribution of the data and the estimated model (Snipes and Taylor 2014). The AICc is preferable to the standard AIC if the number of observations is small. AICc is a powerful method for comparing models and frequently used in model selection (Andrews and Currim 2003, Ingdal et al. 2019, Wagenmakers and Farrel 2004, Jakubczy 2019). Note that the AICc scores are ordinal and dimensionless; they are simply a tool for model ranking (Snipes and Taylor 2014). Additionally, the AICc is used to derive posterior model weights in a Bayesian setting with special prior distribution. Basically, the probability weights are formulated as difference between the AICc of a particular model and the AICc of the model with the minimal AICc. These weights then show the probability that one model fits better than the other models. Thus, the weights can be interpreted similar to p-values in classical hypothesis testing. These probabilities are helpful in case of small differences between AICc scores.

Due to the large number of 33 variations in each alternative model, a stepwise selection process is adopted: First, within each alternative model (i.e., smooth TP, discrete TP, two TP) the AICc for all 33 functional variations is compared and the variation with the lowest AICc is selected. Next, this best fitting functional variation within each alternative model is compared to the AICc of the baseline model. If the baseline model has a higher AICc, the null hypothesis is rejected and the alternative model variation with the lowest AICc is selected as it describes the observed data best. This model then provides the turning point(s) when and how the model shape changes. If the baseline model has the lowest AICc, the null hypothesis is retained as the observed data adhere to the idealized s-shape.

Survey

At the turn of the year 2019/2020, data were collected in an online survey contracted to a commercial online panel provider. The survey population was defined as Austrian homeowners of a detached, semi-detached or terraced house who have their principal residence in this house and who had renovated this house at least once during the last seven years. After excluding fragmentary or negligent responses, the sample comprised n=621 valid cases for analysis.

Respondents were asked to retrospectively reconstruct their building and household history, looking back seven years for eliciting renovations, and ten years for eliciting critical events. Respondents stated the calendar date when a specific event occurred for

- six types of renovations (refurbishing wall insulation, windows, roof insulation, cellar insulation; changing the heating system; installing a photovoltaics or solar heating module),
- four types of building events (breakdown of the heating system, blockage or rupture of water or heating pipes, roof damage, window damage),
- three types of circumstantial events (windfall availability of a large sum of money, availability of more personal time for doing construction work, need of care or physical disability),
- three types of household events (birth of a child, moving in of an adult, moving out or death of an adult),

- and two types of subsidies (by public authorities, by private companies).

Calendar dates were given as years; if known, as quarter of the respective year. In renovations, calendar dates were given separately for the steps of the implementation process: (i) considering the renovation for the first time, (ii) concluding planning, (iii) commencement of construction work, (iv) completion or cessation of construction. The time periods between these steps were calculated as the duration of the planning (i-ii), preparation (ii-iii), construction (iii-iv) and total implementation (i-iv) phases.

Linear multiple regression analysis identifies how strongly critical events influence renovations, regarding the occurrence of a renovation (i.e. the trigger effect of events) and the pace of implementing a renovation (i.e. the accelerator effect of events). Entering all events in a joint regression equation allows determining the unique effect of each event while controlling for the effects of other events; this allows for clearer interpretation as events may co-occur or instigate each other.

Reconstructing critical events as precursors of turning points

A mixed-method approach identified critical events that explain why and when turning points occurred in the diffusion curves of electric cars, heat pumps and photovoltaics. Reconstruction of critical events followed grounded theory principles and procedures (Strauss and Corbin 1998), using the politics, policy and technology stream of each low-carbon technology as initial coding scheme that was gradually extended as evidence accumulated from different sources. A critical event is understood as a focal point in a specific stream that redefined ingrained rules and discourses (e.g. when public mood shifted to favor a particular policy approach or product), that triggered a chain of subsequent events in the same or other streams (e.g. when a strategy document kicked off a bundle of specific measures), or when gradual build-up culminated in a discernible moment of change (e.g. when engineering progress resulted in the market introduction of a new product family).

Critical events were determined in a three-step procedure (Creswell 2009, Johnson et al. 2017). The first step established historical cornerstones and basic developments on a timeline from 1970/1990 to the present. A screening of high-level documents compiled European and national policy strategies, environmental assessment and climate monitoring reports, reviews on technological and market progress, as well as major policy programs and regulation (full list of documents is provided in Table A3). Outstanding events identified in this source material were placed on a timeline together with statistics on technology diffusion (see data description in 3.1). A first round of four semi-structured interviews with key informants from national authorities and trade associations explored these preliminary timelines, pointed out gaps and inconsistencies, added informal aspects not covered by written sources, and directed to further relevant sources (full list of interviewee affiliations is provided in Table 5). Interview audio-records were transcribed and analyzed by applying the above coding scheme; verbatim interview quotes were translated to English by the authors.

The second step added detail to the timelines by in-depth archival research covering scientific literature, market reports, legal documents (e.g. enacted laws, subsidy programs, ministerial decrees) and media statements. In order to improve coverage, the scope of policy measures and actors was widened to the regional/provincial governance level and included studies on similar developments in other countries. In total, 466 documents were analyzed that referenced electric cars, heat pumps or photovoltaics; several climate and energy policy documents addressed all three technologies. The resulting timelines comprised 128 events regarding electric cars, 79 events with respect to heat pumps and 100 events regarding photovoltaics, with each event assigned to either the politics, policy or technology stream (for details see Section 4 – WP2). This was complemented by a second round of five expert interviews (Table 5) who reviewed and contextualized the selection of critical events; interviewee responses were processed as in the first interview round.

The third step concluded an iterative process of narrowing down to a compact selection of critical events. In a workshop with eleven experts (Table 5), the turning points determined in change point analysis (see Section 6 – Change Point Analysis) and the critical events underlying these turning points were scrutinized and validated; in addition, the workshop elaborated cross-cutting issues in terms of communalities and differences between technologies.

A four hour workshop was set up to validate the developed storylines. Interview partners from the round of expert interviews as well as further experts were invited; altogether, participated 11 experts. After presenting the change point analysis and graphic representation of the chronological key events for all three streams and each technology, break out groups discussed key events and timing in more detail to validate, complement or contradict presented findings. A three-step concluding session followed. First, results of the break out groups per technology were presented and critically commented to highlight most important issues. Second, cross-cutting issues in terms of communalities and differences between the three technologies were generated and posted on a wall with the graphic representation of the chronological key events. This was conducted after informal discussions in a market place setting. Third, lessons learnt for the future promotion of low carbon technologies were drawn in a plenary discussion.

Taken together, the three steps of the triangulation procedure consecutively informed each other, enabling cross-checking and synthesis within and between streams and technologies, particularly when reconstructing events and considerations that took place years ago.

Table 5. List of experts

No.	*Affiliation*	*Expertise*	*Participated in*		
			1st interview round	2nd interview round	Workshop
E1	Environment Agency Austria	Electric cars	x		x
E2	Climate and Energy Fund Austria	Electric cars Photovoltaics	x		x
E3	Federal Ministry for Transport, Innovation and Technology, Task Force Mobility Change and Decarbonisation	Electric cars		x	x
E4	Photovoltaics Austria trade association	Photovoltaics	x		
E5	University of Applied Sciences Technikum Vienna	Heat pumps & Photovoltaics		x	
E6	Climate and Energy Fund Austria	Photovoltaics		x	x
E7	Heat Pumps Austria trade association	Heat pumps	x		
E8	Federal Ministry for Sustainability and Tourism, Department Renewable Energy, Electricity & district heating	Heat pumps		x	
E9	Federal Ministry for Sustainability and Tourism, Department Energy Efficiency & Buildings	Heat pumps		x	
Ws	Renewable Energies Austria umbrella association	Heat pumps & Photovoltaics			x
Ws	Austrian Institute of Economic Research	Climate Policy			x
Ws	Executive Office for the Coordination of Climate Protection Measures, City of Vienna	Electric cars			x
Ws	Chamber of Labor Vienna	Climate Policy			x
Ws	University of Natural Resources and Life Sciences Vienna, Center for Global Change and Sustainability	Climate Policy l			x
Ws	World Wide Fund For Nature	Climate Policy			x
Ws	University of Natural Resources and Life Sciences Vienna, Department of Economics and Social Sciences	Climate Policy			x

References

Adner R., 2002. When are technologies disruptive: A demand-based view of the emergence of competition. Strategic Management Journal 23, 667–88.

Akaike, H., 1973. Information Theory and an Extension of the Maximum Likelihood Principle, in: Petrov, B.N., Csaki, F. (Eds), Proceedings of the 2nd International Symposium on Information Theory. Akademiai Kiado, Budapest, pp. 267-81.

Andrews, R., Currim, I., 2003. Retention of latent segments in regression based marketing models. International Journal of Research and Marketing. 20, 315–21.

Austria Tech, 2016. Elektromobilität 2015: Monitoringbericht. Austria Tech, Wien (downloaded on 26 March 2020 from https://www.austriatech.at/assets/Uploads/Themen/Publikationen/Files/3c1164fdab/Elektromobilitaet-2015-Monitoringbericht.pdf).

Bass, F.M., 1969. A new product growth for model consumer durables. Management Science 15, 215–27.

Biermayr, P., Dißauer, C., Eberl, M., Enigl, M., Fechner, H., Fischer, L., Fürnsinn, B., Leonhartsberger, K., Moidl, S., Schmidl, C., Strasser, C., Weiss, W., Wonisch, P., Wopienka, E., 2019 , Innovative Energietechnologien in Österreich: Marktentwicklung 2018. Berichte aus Energie- und Umweltforschung 20/2019, Wien.

BMLFUW, BMVIT, BMWFJ, 2012. Umsetzungsplan Elektromobilität in und aus Österreich. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Wien.

BMLFUW, BMVIT, BMWFJ, 2016. Nationaler Strategierahmen: Saubere Energie im Verkehr, Wien.

BMNT 2017. Maßnahmen im Gebäudesektor 2016. Bericht des Bundes und der Länder nach Art. 15a B-VG Vereinbarung Bgbl. II Nr. 251/2009. Bundesministerium für Nachhaltigkeit und Tourismus, Wien.

BMNT, 2019. Photovoltaik-Land Österreich. Retrieved from: https://www.bmnt.gv.at/umwelt/energiewende/erneuerbare_energie/Photovoltaik-Land-Österreich.html

BMWFJ, BMLFUW, 2010. Energiestrategie Österreich 2010 (downloaded on 26 March from https://nachhaltigwirtschaften.at/de/e2050/ueber-energie-2050/energiestrategie-oesterreich.php).

BMWV, 1998. Verbreitung der Photovoltaik in Österreich: Der 200-KW-Photovoltiak-Breitentest Soziologische Breitenforschung. Forschungsforum 2/98 Energie, Wien.

Böckers, V., Heimeshoff,U., Müller, A., 2012. Pull-forward effects in the German car scrappage scheme: A time series approach. DICE Discussion Papers 56, University of Düsseldorf, Düsseldorf Institute for Competition Economics (DICE).

Boswell, C., Rodrigues, E., 2016. Policies, politics and organisational problems: Multiple streams and the implementation of targets in UK government. Policy & Politics 44, 507-24(18). https://doi.org/10.1332/030557315X14477577990650

Brunner, S., 2008. Understanding policy change: Multiple streams and emission trading in Germany. Global Environmental Change 18, 501-07. https://doi.org/10.1016/j.gloenvcha.2008.05.003

Buchegger, A., 2018. Österreichs Klimastrategien: Von den Anfängen über das Kyoto-Protokoll bis hin zur Paris-Umsetzung, Umweltschutz der Wirtschaft Spezial 18, 48-49.

BMHGI, 1979. Energiebericht 1979: Zweite Anpassung des Energieplans. Bundesministerium für Handel, Gewerbe und Industrie, Wien (downloaded on 26 March 2020 from https://www.parlament.gv.at/PAKT/VHG/XV/III/III_00001/imfname_555507.pdf).

Carter, N. and Jacobs, M., 2014, Explaining Radical Policy Change: The Case of Climate and Energy Policy Under the British Labour Government 2006-10. Public Admin 92, 125-41. https://doi.org/10.1111/padm.12046

Cherp A., Vinichenko, V., Jewell, J., Brutschin, E., Sovacool, B., 2018. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework, Energy Research & Social Science 37, 175-90. https://doi.org/10.1016/j.erss.2017.09.015.

Cherp, A. and Adenikinju, A. and Goldthau, A. and Hernandez, F. and Hughes, L. and Jansen, J. and Jewell, J. and Olshanskaya, M. and Oliveira, R. and Sovacool, B. & Vakulenko, S. (2012). Energy and security, in: Global Energy Assessment: Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 325-83.

Collantes, G., Sperling, D., 2008. The origin of California's zero emission vehicle mandate. Transportation Research Part A: Policy and Practice 42, 1302-13. https://doi.org/10.1016/j.tra.2008.05.007.

Cooper-Searle, S., Livesey, F., Allwood, J.M., 2018.Why are material efficiency solutions a limited part of the climate policy agenda? An application of the multiple streams framework to UK policy on CO2 emissions from cars. Environmental Policy and Governance 28, 51–64. https://doi.org/10.1002/eet.1782

Creswell, J., 2009. Research design. Qualitative, quantitative and mixed methods approaches. Los Angeles: Sage.

Devezas, T., LePoire, D., Matias, J., Silva, A., 2008. Energy scenarios: Toward a new energy paradigm, Futures 40, 1-16. https://doi.org/10.1016/j.futures.2007.06.005

Dong, C., Sigrin, B., Brinkman, G., 2017. Forecasting residential solar photovoltaic deployment in California. Technological Forecasting and Social Change 117. https://doi.org/10.1016/j.techfore.2016.11.021

Ducoterra 2014. Heating System Cost and Performance Analysis (downloaded on 25 March 2020 from https://heatinggreen.com/wp-content/uploads/2017/09/Efficiency-Analysis.pdf).

EEA, 2019, Greenhouse gas emissions from transport in Europe, Maps and Indicators, European Environment Agency, Copenhagen.

EHPA, 2009, European heat pump statistics: Outlook 2009. European Heat Pump Association, Brussels (downloaded on 26 March 2020 from https://www.ehpa.org/fileadmin/red/07._Market_Data/2008/EHPA_Heat_Pump_Outlook_2009.pdf).

European Commission, 2014. A policy framework for climate and energy in the period from 2020 to 2030. COM(2014) 15 final. European Commission, Brussels (downloaded 26 March 2020 from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52014DC0015).

Faninger, G., 2007. Der Photovoltaikmarkt in Österreich 2006. Bundesministerium für Verkehr, Innovation und Technologie, Wien.

Fisher, J. C., Pry, R. H., 1971. A simple substitution model of technological change. Technology Forecasting and Social Change 3, 75–88.

Fraunhofer ISE, 2018. Stromgestehungskosten Erneuerbare Energien. Fraunhofer-Institut Für Solare Energiesysteme ISE, Freiburg (downloaded on 26 March 2020 form https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/DE2018_ISE_Studie_Stromgestehungskosten_Erneuerbare_Energien.pdf)

Frieden, D., 2019, Verfügbarkeit und Qualität von Photovoltaikanlagen-Statistiken in Österreich. Sonne, Wind und Wärme, Heft 15/ 2019.

Geels, F., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Research Policy 31, 1257-74. https://doi.org/10.1016/S0048-7333(02)00062-8

Gilli, P., Schabkar, F., Halozan, H., 1978. Verringerung des Energieaufwandes mit Hilfe von Wärmepumpen, Graz.

Glöckel, T., 1997. Alternativ Betriebene Fahrzeuge in Österreich: Eine Bestandsaufnahme. Bundesministerium für Umwelt, Jugend und Familie, Wien. (downloaded on 26 March 2020 from https://www.umweltbundesamt.at/fileadmin/site/publikationen/R141.pdf).

Gnann, T., Stephens, T.S., Lin, Z., Plötz, P., Liu, C., Brokate, J., 2018. What drives the market for plug-in electric vehicles? A review of international PEV market diffusion models.

Renewable and Sustainable Energy Reviews 93, 158-64. https://doi.org/10.1016/j.rser.2018.03.055
Grossman, P.Z., 2015. Energy shocks, crises and the policy process: A review of theory and application. Energy Policy 77, 56-69. https://doi.org/10.1016/j.enpol.2014.11.031.
Guidolin, M., Mortarino, C., 2010. Cross-country diffusion of photovoltaic systems: modelling choices and forecasts for national adoption patterns. Technological Forecasting and Social Change 77, 279–96. https://doi.org/10.1016/j.techfore.2009.07.003
Harris, T. M., Devkota, J. P., Khanna, V., Eranki, P. L., Landis, A. E., 2018. Logitstic growth curve modeling of US energy production and consumption. Renewable and Sustainable Energy Reviews 96, 46-57. https://doi.org/10.1016/j.rser.2018.07.049
Heimdal, S.I., 2011. Reliability of air to air heat pumps and their contribution to energy savings in Norway. Energy Efficiency First: The Foundation of a Low-Carbon Society. Proceedings of the ECEEE Summer Study 2011, 1807-1813.
IEA, 2019. World Energy Outlook 2019. International Energy Agency, Paris
Ingdal, M., Johnsen, R., Harrington, D.A., 2019. The Akaike information criterion in weighted regression of immittance data. Electrochimica Acta 317, 648-53. https://doi.org/10.1016/j.electacta.2019.06.030.
IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.
IPCC, 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (Eds)]. In Press.
Jakubczyk, T., 2019. Analysis of distribution of precipitation duration and amounts in Legnica in the period 1966-2015. Journal of Water and Land Development 41 (IV-VI), 69-76. https://doi.org/10.2478/jwld-2019-0029.
Johnson, R. B., Russo, F., Schoonenboom, J., 2017. Causation in Mixed Methods Research: The Meeting of Philosophy, Science, and Practice. Journal of Mixed Methods Research 13, 143-62. https://doi.org/10.1177/1558689817719610
Kapusta, F., Karner, A., Heidenreich, M., 2002. 200 kW Photovoltaik-Breitentest. Berichte aus Energie- und Umweltforschung 16/2002, Bundesministerium für Verkehr, Innovation und Technologie, Wien (downloaded on 26 March 2020 from https://www.nachhaltigwirtschaften.at/resources/nw_pdf/0216_pv_breitentest.pdf).
Keichel, M., Schwedes, O., 2013. Das Elektroauto: Mobilität im Umbruch. Springer Vieweg, Wiesbaden. https://doi.org/10.1007/978-3-658-00796-6
Kingdon, J., 1984. Agendas, Alternatives, and Public Policies. Longman, Harlow.
Kiss, B., Neij, L., Jakob, M., 2011. Heat pumps: A comparative assessment of innovation and diffusion policies in Sweden and Switzerland. https://doi.org/10.1017/CBO9781139150880.013.
KLIEN, 2008. Förderaktion Photovoltaik: Häufig gestellte Fragen zur Förderaktion Photovoltaik-Anlagen (downloaded on 26 March 2020 from https://www.klimafonds.gv.at/wp-content/uploads/sites/6/HaeufiggestellteFragen2.pdf).
KLIEN, 2010. E-connected Abschlussbericht 2010. Klima- und Energiefonds, Wien (downloaded on 26 March from https://www.klimafonds.gv.at/wp-content/uploads/sites/6/KLIENAbschlussberichte-connectedII.pdf)
KLIEN, 2015. Leitfaden für Photovoltaik-Anlagen. Eine Förderaktion des Klima- und Energiefonds der österreichischen Bundesregierung. Klima- und Energiefonds, Wien (downloaded on

26 March 2020 from https://www.klimafonds.gv.at/wp-content/uploads/sites/6/LF-Photovoltaik-2015.pdf)

KLIEN, 2016. Modellregionen der Elektromobilität in Österreich. Klima- und Energiefonds, Wien (downloaded on 26 March 2020 from https://www.klimafonds.gv.at/wp-content/uploads/sites/6/6JahreModellregionenE-MobWebVersion.pdf).

Koarik, A., (2011, 15 Dezember). Vienna Autoshow 2012 in der Messe Wien: Die Automobil-Höhepunkte des Jahres 2012 (downloaded 26 March from https://www.messe.at/presse/pressetext.html?id=1079&messecode=asw).

Kobos, P.H., Malczynski, L.A., Walker, L.T.N., Borns, D.J., Klise, G.T., 2018. Timing is everything: A technology transition framework for regulatory and market readiness levels. Technological Forecasting and Social Change 137, 211-225. https://doi.org/10.1016/j.techfore.2018.07.052.

Kulmer, V., Kortschak, D., Seebauer, S. (in press): Trigger or time fuse? An empirical methodology for detecting change points and pace in the diffusion of low-carbon technologies. In: Zachariadis, T., Milne, J., Andersen, M., Ashiabor, H. (Eds.): Economic instruments for a low carbon future. Critical Issues in Environmental Taxation Vol. XXII, pp-pp, Edward Elgar Publishing.

Kurdgelashvili, L., Shih, C.H. Yang, F., Garg, M., 2019. An empirical analysis of county-level residential PV adoption in California. Technological Forecasting and Social Change 139, 321-33. https://doi.org/10.1016/j.techfore.2018.11.021.

Kurze, K., Lenschow, A. 2018. Horizontal policy coherence starts with problem definition: Unpacking the EU integrated energy-climate approach. Environmental Policy and Governance 28, 329–38. https://doi.org/10.1002/eet.1819

Lee, D.H., Park, S.Y., Kim, J.W., Lee, S.K., 2013. Analysis on the feedback effect for the diffusion of innovative technologies focusing on the green car. Technological Forecasting and Social Change 80, 498-509. https://doi.org/10.1016/j.apenergy.2012.09.046.

Lorenzoni, I., Benson, D., 2014. Radical institutional change in environmental governance: Explaining the origins of the UK Climate Change Act 2008 through discursive and streams perspectives. Global Environmental Change 29, 10-21. http://dx.doi.org/10.1016/j.gloenvcha.2014.07.011

Michalakelis, C., Varoutas, D., Sphicopoulos, T., 2008. Diffusion models of mobile telephony in Greece. Telecommunications Policy 32, 234-245. https://doi.org/10.1016/j.telpol.2008.01.004

Niedertscheider, M., Haas, W., Görg, C., 2018. Austrian climate policies and GHG-emissions since 1990: What is the role of climate policy integration? Environmental Science and Policy 81, 10-17. https://doi.org/10.1016/j.envsci.2017.12.007

Nill, J., 2002. Wann benötigt Umwelt-(innovations)politik politische Zeitfenster? IOW-Diskussionspapier 54/02.

Nilsson, M., Weitz, N., 2019. Governing Trade-Offs and Building Coherence in Policy-Making for the 2030 Agenda. Politics and Governance 7, 254-263. https://doi.org/10.17645/pag.v7i4.2229

Nyborg, S., Røpke, I.,2015. Heat pumps in Denmark: From ugly duckling to white swan. Energy Research and Social Science 9, 166-77. https://doi.org/10.1016/j.erss.2015.08.021

Nykvist B, Nilsson M., 2015. Rapidly falling costs of battery packs for electric vehicles. Nature Climate Change 5, 329–32.

Oughton, E., Frias, Z., Russell, T., Sicker, D., Cleevely, D., 2018. Towards 5G: Scenario-based assessment of the future supply and demand for mobile telecommunications infrastructure. Technological Forecasting and Social Change 133, 141-155. https://doi.org/10.1016/j.techfore.2018.03.016

Österreichischer Städtebund, 2010. Elektromobilität in Städten und Regionen. ÖGZ 4/2010 (downloaded on 26 March 2020 from https://www.staedtebund.gv.at/ePaper/oegz-2010-04/#p=1).

Pfaffenbichler, P.C., Emmerling, B., Jellinek, R., Krutak, R., 2009. Pre-Feasability-Studie zu Markteinführung Elektroautomobilität in Österreich. Austrian Energy Agency, Wien (downloaded on 26 March 2020 from https://www.energyagency.at/fileadmin/dam/pdf/publikationen/berichteBroschueren/Endbericht-markteinfuehrung_emobilitaet.pdf).

PVA, 2019. Gemeinsam Stark. Photovoltaik Österreich, Wien (downloaded on 26 March 2020 from https://www.pvaustria.at/wp-content/uploads/2019-02-18-Bilanzbroschüre-2019-final.pdf).

Rogers, E. M., 1983. Diffusion of innovations (3rd Edition). Free Press, New York.

Sartori, I., Wachenfeldt, B. J., Hestens, A. G., 2009. Energy demand in the Norwegian building stock: Scenarios on potential reduction. Energy Policy 37, 1616-27. https://doi.org/10.1016/j.enpol.2008.12.031

Scarlat, N., Dallemand, J.-F., Monforti-Ferrario, F., Banja, M., Motola, V., 2015. Renewable energy policy framework and bioenergy contribution in the European Union: An overview from national renewable energy action plans and progress reports. Renewable and Sustainable Energy Reviews 51, 969-85. https://doi.org/10.1016/j.rser.2015.06.062

Simpson, G., Clifton, J., 2017. Testing diffusion of innovations theory with data: Financial incentives, early adopters, and distributed solar energy in Australia. Energy Research and Social Science 29, 12-22. https://doi.org/10.1016/j.erss.2017.04.005.

Snipes, M., Taylor, D.C., 2014. Model selection and Akaike Information Criteria: An example from wine ratings and prices, Wine Economics and Policy 3, 3-9. https://doi.org/10.1016/j.wep.2014.03.001

Sood A., Tellis G., 2005. Technological Evolution and Radical Innovation. Journal of Marketing 69, 152-68. https://doi.org/10.1509/jmkg.69.3.152.66361

Statistics Austria, 2018. Stock of motor vehicles 1990-2018

Steininger, K., König, M., Bednar-Friedl, B., Kranzl, L., Loibl, W., Prettenthaler, F. (2014). Economic Evaluation of Climate Change Impacts: Development of a Cross-Sectoral Framework and Results for Austria. Springer, Berlin.Stern, N., 2006. The Economics of Climate Change: The Stern Review; Summary of Conclusions

Steurer, R., 2013. Disentangling governance: A synoptic view of regulation by government, business and civil society. Policy Sciences 46, 387–410. https://doi.org/10.1007/s11077-013-9177-y.

Strauss, A., Corbin, J.M., 1998. Basics of qualitative research: techniques and procedures for developing grounded theory. SAGE, Thousand Oaks.

SVEP, 2007. Small-Scale Ground Source Heat Pumps on the Swedish Market [Online]. Swedish Heat Pump Association.

Teoh, M., Liebl, V., 2016. Leitfaden zu PV-Eigenverbrauchsmodellen: Projekt PV Financing (downloaded on 26 March 2020 from https://www.pvaustria.at/wp-content/uploads/2017-11-28-PV-Leitfaden-Eigenverbrauch-Auflage_4.pdf).

UBA, 2006. Evaluierungsbericht zur Klimastrategie 2002. Report, Bd. REP-0021. Umweltbundesamt, Wien.

UBA, 2015. CO2-Monitoring Pkw 2015. Bericht über die CO2-Emissionen neu zugelassener Pkw in Österreich.Umweltbundesamt, Wien.

UBA, 2016. Elfter Umweltkontrollbericht: Umweltsituation in Österreich. Report, Bd. REP-0600. Umweltbundesamt, Wien (downloaded on 26 March 2020 from https://www.umweltbundesamt.at/fileadmin/site/publikationen/REP0600.pdf).

UBA, 2018. Klimaschutzbericht 2018. Report, Bd. REP-0660. Umweltbundesamt, Wien (downloaded on 26 March 2020 from https://www.umweltbundesamt.at/fileadmin/site/publikationen/REP0660.pdf).

UN, 2015. The Paris Agreement (downloaded on 26 March 2020 from https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf).

UNTC, 1998. Kyoto Protocol to the United Nations Framework Convention on Climate Change. United Nations, Kyoto (downloaded on 26 March 2020 from https://treaties.un.org/doc/Publication/MTDSG/Volume%20II/Chapter%20XXVII/XXVII-7-a.en.pdf).

van der Kam, M.J., Meelen, A.A.H., van Sark, W.G.J.H.M., Alkemade, F., 2018. Diffusion of solar photovoltaic systems and electric vehicles among Dutch consumers: Implications for the energy transition. Energy Research and Social Science 46, 68-85. https://doi.org/10.1016/j.erss.2018.06.003

Vynakov, O.F., Savolova, E.V., Skrynnyk, A.I., 2016. Modern electric cars of tesla motors company. Automation of Technological and Business-Processes 8, 9-18. https://doi.org/10.15673/atbp.v8i2.162

Wagenmakers, E.-J., Farrel S., 2004. AIC model selection using Akaike weights. Psychonomic Bulletin and Review 11, 192–6. https://doi.org/10.3758/bf03206482

WPZ, 2001. COP Values, Wärmepumpen-Testzentrum Töss. WPZ Bulletin.

Xu, J., Li, L., Zheng, B., 2016. Wind energy generation technological paradigm diffusion. Renewable and Sustainable Energy Reviews 59, 436-49. https://doi.org/10.1016/j.rser.2015.12.271

Zhang, S., He, Y., 2013. Analysis on the development and policy of solar PV power in China. Renewable and Sustainable Energy Reviews 21, 393-401. https://doi.org/10.1016/j.rser.2013.01.002

Zhou, H., Yang, Z., 2018. Comparison of fuel-efficiency technology deployment in passenger cars in China, Europe, and the United States. ICCT, Beijing (downloaded on 26 March 2020 from https://theicct.org/sites/default/files/publications/PV_efficiency_China_EU_US_20180615.pdf).

Zohlnhöfer, R., Herweg, N., Rüb, F., 2015. Theoretically refining the multiple streams framework: An introduction. European Journal of Political Research 54, 412-418. https://doi.org/10.1111/1475-6765.12102

Media outlets

derstandard.at, 2012. 2012 war teuerstes Tankjahr. Available at https://www.derstandard.at/story/1356426367466/2012-war-teuerstes-tankjahr (accessed on 26 March 2020).

spiegel.de, 2011.Tesla Roadster 2.5 Sport: Wer rasen will, muss planen. Available at https://www.spiegel.de/auto/fahrberichte/tesla-roadster-2-5-sport-wer-rasen-will-muss-planen-a-763868.html (accessed on 262 March 2020).

Laws and regulations on EU level

Council Directive 96/92/EC concerning common rules for the internal market in electricity. Official Journal of the European Communities L27, 20-29 (available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31996L0092&from=DE).

Council Directive 2001/77/EC on the promotion of electricity produced from renewable energy sources. Official Journal of the European Communities L283, 33-40 (downloaded 26 March from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32001L0077&from=EN).

Council Directive 2002/91/EC on the energy performance of buildings. Official Journal of the European Communities L1, 65-71 (available https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:001:0065:0071:EN:PDF).

Council Directive 2009/28/EC on the promotion of the use of energy from renewable sources. Official Journal of the European Communities L140, 16-62 (available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0028&from=DE).

Council Directive 2010/31/EU on the energy performance of buildings (recast). Official Journal of the European Communities L153, 13-25 (available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0031&from=EN)

Council Directive 2014/94/EU on the deployment of alternative fuels infrastructure. Official Journal of the European Communities L307, 1-20 (available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0094&from=EN).

Council Implementing Regulation (EU) No 1238/2013 imposing a definite anti-dumping duty and collecting definitely the provisional duty imposed on imports of crystalline silicon photovoltaic modules and key components (i.e. cells) originating in or consigned from the People's Republic of China. Official Journal of the European Communities L325, 1-65 (available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013R1238&from=DE).

Council Regulation (EC) No 443/2009 setting emission performance standards for new passenger cars as part of the Community`s integrated approach to reduce CO2 emissions from light-duty vehicles. Official Journal of the European Communities L140, 1-15 (available https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009R0443&from=EN).

Council Regulation (EU) 333/2014 amending Regulation (EC) No 443/2009 to define the modalities for reaching the 2020 target to reduce CO2 emissions from new passenger cars. Official Journal of the European Communities L103, 15-21 (available https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R0333&from=EN).

Proposal for a Council Regulation COD/2007/0297 setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO2 emissions from light-duty vehicles. Commission of the European Communities, Brussels (available at https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2007:0856:FIN:EN:PDF).

Treaty (94/C 241/07) concerning the accession of the Kingdom of Norway, the Republic of Austria, the Republic of Finland and the Kingdom of Sweden to the European Union. Official Journal of the European Communities C241, 9-404 (available at https://eur-lex.europa.eu/resource.html?uri=cellar:6a09c1b5-b835-42e7-9901-0c33354bf77b.0008.03/DOC_1&format=PDF).

Laws and regulation on Austrian national and provincial level

Agreement between the federal government and the states on saving energy. In:Federal Law Gazette 388/1995 (available at https://www.ris.bka.gv.at/Dokumente/BgblPdf/1995_388_0/1995_388_0.pdf).

Agreement between the federal government and the states on common quality standards for subsidizing building and refurbishment of residential buildings. In: Federal Law Gazette II No 19/2006 (available at https://www.ris.bka.gv.at/Dokumente/BgblAuth/BGBLA_2006_II_19/BGBLA_2006_II_19.html).

Amendment to the Green Electricity Act 2006. In: Federal Law Gazette I No 105/2006. (available at https://www.ris.bka.gv.at/Dokumente/BgblAuth/BGBLA_2006_I_105/BGBLA_2006_I_105.html).

Amendment (2nd) to the Green Electricity Act 2008. In: Federal Law Gazette I No 114/2008. (available at https://www.ris.bka.gv.at/Dokumente/BgblAuth/BGBLA_2008_I_114/BGBLA_2008_I_114.html).

Amendment to the Housing Improvement Act. In: Federal Law Gazette I No 337/1978. 337 (available at https://www.ris.bka.gv.at/Dokumente/BgblPdf/1978_337_0/1978_337_0.pdf).

Amendment to the Vienna Building Code (Bauordnung für Wien bzw. Wiener Garagengesetz). In: Provincial Law Gazette No 96/2018 (available at https://www.ris.bka.gv.at/Dokumente/LgblAuth/LGBLA_WI_20181221_69/LGBLA_WI_20181221_69.html).

Climate and Energy Fund Act (KLI.EN-FondsG). In: Federal Law Gazette I No 40/2007 (avaible at https://www.ris.bka.gv.at/Dokumente/BgblAuth/BGBLA_2007_I_40/BGBLA_2007_I_40.html)

Climate Change Act (KSG). In: Federal Law Gazette I No 106/2011 (available at https://www.ris.bka.gv.at/Dokumente/BgblAuth/BGBLA_2011_I_106/BGBLA_2011_I_106.html).

Electricity Business and Organisation Act. In: Federal Law Gazette I No 143/1998 (available at https://www.ris.bka.gv.at/Dokumente/BgblPdf/1998_143_1/1998_143_1.pdf).

Green Electricity Act 2002. In: Federal Law Gazette I No 149/2002. (available at https://www.ris.bka.gv.at/Dokumente/BgblPdf/2002_149_1/2002_149_1.pdf).

German Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz - EEG. In: Federal Law Gazette 13/2000 (available at http://www.bgbl.de/xaver/bgbl/start.xav?startbk=Bundesanzeiger_BGBl&jumpTo=bgbl100s0305.pdf).

International Energy Agency Implementation agreement for a research and development programme for heat pumps. In: Federal Law Gazette 214/1980 (available at https://www.ris.bka.gv.at/Dokumente/BgblPdf/1980_214_0/1980_214_0.pdf).

Mineral Oil Tax 1995. In: Federal Law Gazette No 630/1994 (available at https://www.ris.bka.gv.at/Dokumente/BgblPdf/1994_630_0/1994_630_0.pdf).

Tax Reform Act 2015/16 (StRefG 2015/2016). In: Federal Law Gazette I No 118/2015 (available at https://www.ris.bka.gv.at/Dokumente/BgblAuth/BGBLA_2015_I_118/BGBLA_2015_I_118.html).

7 Work and time schedule

	2017										2018											
	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
WP1	M1.1						M1.2					M1.2	M1.3						M1.2			
WP2										M2.1										M2.2		
WP3										M3.1					M3.2							
WP4																						
WP5																						
WP6		M6.1 M6.2											M6.3									

	2019										
	1	2	3	4	5	6	7	8	9	10	12
WP1		M1.2					M1.2				M1.24
WP2											
WP3											
WP4	M4.1				M4.2		M4.3				
WP5			M5.2		M5.3				M5.4		
WP6											M6.4 M6.5

The project was extended until December 31 2019 due to V. Kulmer’s paternal leave from June 2018 to June 2019. This extension enabled a well-founded analysis of results and the preparation of a high-quality research article submitted for publication that clear the peer review hurdle (see below).

8 Publications and dissemination activities

Published articles, Papers under review and working papers

Kulmer V., Seebauer S., Hinterreither H., Kortschak D., Theurl M., Haas W., (2020, under review), Beyond the s-shape: explaining turning points in market diffusion of low-carbon technologies by means of political, policy and technology streams. *Working Paper*. Available at: https://timelag.joanneum.at

Kulmer V., Kortschak D., Seebauer S. (in press), Trigger or time fuse? An empirical methodology for detecting change points and pace in the diffusion of low-carbon technologies. In: Zachariadis, T., Milne, J., Andersen, M., Ashiabor, H. (Eds.): Economic instruments for a low carbon future. Critical Issues in Environmental Taxation Vol. XXII, Edward Elgar Publishing.

Frieden, D. (2019), Verfügbarkeit und Qualität von Photovoltaikanlagen-Statistiken in Österreich, Sonne, Wind und Wärme, Heft 15/ 2019.

https://www.sonnewindwaerme.de/ausgabe/ausgabe-152019-sonderteil-building-automation-42019

Seebauer S. (2020), Critical events as triggers and accelerators of building renovations in private residential buildings. *Working Paper*. Available at: https://timelag.joanneum.at

Talks and posters at scientific conferences and international workshops

Venue	Description
Austrian Climate Day 2018 in Salzburg, 23-25 April S. Seebauer	Poster presentation to the ACRP steering committee Veronika Kulmer, Sebastian Seebauer, Willi Haas, Michaela Theurl, Temporal dynamics between policy design, implementation and market diffusion of low carbon technologies
International Sustainability Transitions (IST) 2018 Conference, 12-14 June, Manchester S. Seebauer	Oral presentation Sebastian Seebauer, Veronika Kulmer, Willi Haas, Michaela Theurl, Time lags between policy implementation and market diffusion: An empirical framework for low-carbon technological change in Austria.
Conference on Impact of Research and Innovation Policy at the Crossroads of Policy Design, Implementation and Evaluation, 5-6 Nov 2018, Vienna S. Seebauer	Oral presentation Sebastian Seebauer, Veronika Kulmer, Willi Haas, Michaela Theurl, How long does it take for a policy to affect the market? Analysing time lags in low-carbon technological change in Austria
Global Conference of Environmental Taxation, 25 – 28 September 2019, Cyprus V. Kulmer (talk had been cancelled due to illness)	Oral presentation Kulmer V., Kortschak D., Seebauer S., Trigger or time fuse? An empirical methodology for detecting change points and pace in the diffusion of low-carbon technologies
Austrian Climate Day 2020 in Leoben, 2-4 Sept (forthcoming) V. Kulmer	Oral presentation Kulmer V., Seebauer S., Hinterreither H., Kortschak D., Theurl M., Haas W., Beyond the s-shape: explaining turning points in market diffusion of low-carbon technologies by means of political, policy and technology streams

Project webpage

https://timelag.joanneum.at/

Project workshop

Stakeholder and Expert Workshop, November 22nd, Vienna

Policy brief for target groups

Available at https://timelag.joanneum.at/policybrief

Talks at national as well as international stakeholder meetings and networks

COP23 climate conference, 2017, Bonn, W. Haas	Discussion project rationale and preliminary findings with international policymakers and experts
Klima:aktiv podium discussion, 2017, Vienna W. Haas	Exchange of vies regarding - mobility and sustainable building; Getting in contact with potential interview partner,
Expert workshop, organized by Automotive Cluster Styria, 22 Nov 2018, Graz S. Seebauer	Keynote lecture on climate policy impacts on the market environment of conventional and electric vehicles
Change! workshop, organized by Urban Mobility Lab Salzburg, 15 Jan 2020, Salzburg S. Seebauer	Keynote lecture on structural and personal drivers of market diffusion of electric vehicles
VCÖ Round table "Transformation of mobility", 2019, Vienna, V. Kulmer	Oral presentation of project findings regarding e-car diffusion;

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