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How Policy Mixes Shape Technological Change and Organizational Learning in the Energy Sector

The Case of Distributed Energy Resources

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“The concept of global warming was created by and for the Chinese
in order to make U.S. manufacturing non-competitive.”

Donald J. Trump, 2012, Twitter

“This very expensive GLOBAL WARMING bullshit has got to stop.
Our planet is freezing, record low temps,and our GW scientists are stuck in ice.”

Donald J. Trump, 2014, Twitter

“The fundamental cause of the trouble is that in the modern world
the stupid are cocksure while the intelligent are full of doubt.”

Bertrand Arthur William Russell, 1933, “The Triumph of Stupidity”

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Abstract

A fundamental technological transformation in the energy sector is widely seen as a prerequisite of effective climate change mitigation. In light of the urgency of global warming, public policy plays a central role in accelerating this "energy transition", which requires overcoming numerous technological, economic, social and institutional challenges. However, due to the complexity of socio-technical change in the energy sector, successfully governing this transition necessitates a holistic approach rather than fixing individual issues with a patchwork of isolated policy instruments that may undermine each other. As a result, designing more effective "policy mixes", i.e. several policy instruments embraced by an overarching policy strategy, gains increasing importance.

To support policy makers in developing these sophisticated governing tools, this dissertation aims at augmenting our understanding of *how policy mixes affect technological change and organizational learning in the energy sector*. To shed light on this question, the thesis adopts the perspective of three key stakeholders, namely policy makers, firms and end consumers, by combining and building on the insights from political science, innovation studies, and organizational theory.

This work draws on empirical data from the domain of distributed energy resources (DER), more precisely residential solar photovolatic (PV) and energy storage systems. This case has been selected since DER carry the potential to trigger an unprecedented downstream shift of value in the energy sector, which has strong implications for sectoral change as well as for incumbents and new entrants developing new business models. The confluence of multiple technologies, applications and end consumer heterogeneity, renders policy making an intricate task. This is why a thorough assessment of the corresponding policy mix and its co-evolution with the DER domain may yield important insights for policy makers and analysts. Moreover, the changing business environment requires incumbent firms to redefine their strategies and adapt their core capabilities, which makes the changing DER domain a great case to observe and derive rich insights into alternative organizational learning approaches.

To explore and illustrate the interplay between policy makers, firms, and end consumers in the context of DER, this dissertation applies a mix of both qualitative and quantitative methods, including single and multiple case study research, as well as techno-economic and agent-based modelling. In line with this approach, the overarching research question is broken into four components, each addressing a distinct gap in the literature. The first paper scrutinizes the detailed mechanisms through which the design features of an individual policy instrument affect the impact of a larger policy mix geared towards supporting the economics of a particular DER. The second paper examines how policy-induced technological change shapes the business environment of incumbent firms, and thereby prompts them to pursue particular forms of organizational learning. The third paper elaborates on two conceptual approaches to derive and study the elements of real-world policy mixes. Finally, the fourth paper studies the co-evolution between policy mixes, technology diffusion, and sectoral change with a particular focus on the aspect of multiple policy goals.

This dissertation entails four distinct contributions to the extant literature. First, an analytical framework is presented that may facilitate future research on policy mixes by providing clear guidelines for how to delineate the elements of a policy mix independent of its context. Second, this thesis adds to the policy mix literature by providing suggestions for how to quantify the combined impact of multiple policy instruments both ex post and ex ante. Third, the work emphasizes the role of actors – most importantly policy makers and stakeholders driving technological change – in shaping policy mixes, thereby providing a more nuanced perspective on vertical and horizontal coordination challenges. Fourth, this dissertation addressing a long-lasting puzzle among scholars interested in organizational learning, namely which characteristics of the business environment explain which approaches firms use in order to become ambidextrous, i.e. to overcome tensions from simultaneously exploiting current capabilities and resources, while exploring new business opportunities. In particular, the thesis illustrates that the response of incumbent firms to policy-induced changes in their business environment is contingent upon the nature of the environmental change, which is captured in a comprehensive theoretical framework. The novel concept 'hybrid ambidexterity' reflects the observation that firms may combine previously described structural and contextual approaches when the environment holds numerous uncertain opportunities that are distant from the existing organizational capabilities and culture.

Based on these contributions, the thesis provides a number of valuable insights for practitioners. First, while the impact of a single policy may already be difficult to assess, the evaluation of a multi-goal, multi-instrument policy mix becomes even more challenging. Therefore, this thesis suggests policy makers and analysts to complement 'traditional' policymaking approaches with computation-based analyses such as the quantitative modelling tools developed in this dissertation. Second, in the absence of a clear vision for the role of DER in a changing energy system, an accelerated uptake of these technologies may lead to arbitrary lock-ins into certain socio-technical configurations that are sub-optimal in the longer term. Hence, policy makers should develop a prosumer strategy and align policy instruments accordingly, in order to leverage the full potential of DER for the energy system and society. Third, given the large number and high uncertainty associated with DER technologies, policy makers should promote policy initiatives that integrate the expertise of a wide range of stakeholders – whose interplay determines the pace and direction of technology development and diffusion – into the policy making process. Fourth, corporate managers could apply a key lesson from the case of incumbent utilities in Germany, namely to be careful not to apply premature interpretations of a changing business environment in terms of which opportunities to pursue or to ignore. In this regard, the framework developed in this thesis allows decision makers to make sense of their changing business environment and get an overview of the forms of organizational responses at their disposal. Fifth, the emerging DER domain confronts end consumers with a surge of novel technologies and services. Thus, they should carefully assess the different DER investment options, make use of available policy support and be aware of the different level of maturity. In particular, they should consider important aspects such as compatibility between components, and ease of upgrades, while taking the blurring boundaries between the energy, building, and transport sector into account.

Zusammenfassung

Ein tiefgreifender technologischer Wandel im Energiesektor gilt als eine der Voraussetzungen für einen effektiven Klimaschutz. Im Angesicht der Dringlichkeit der Erderwärmung spielen Politikmaßnahmen eine zentrale Rolle bei der Beschleunigung dieser „Energiewende“, was ein Überwinden zahlreicher technologischer, ökonomischer, sozialer und institutioneller Herausforderungen nötig macht. Die Komplexität eines solchen sozio-technischen Wandels im Energiesektor setzt allerdings voraus, dass das die politischen Maßnahmen im Rahmen eines umfassenden Ansatzes untereinander koordiniert werden, um die Entstehung eines Flickwerks aus Partikularlösungen für einzelne Probleme zu vermeiden. Daher wird der Entwicklung von „Policy Mixes“ – mehrere Instrumente, die durch eine übergreifende Strategie umfasst sind – eine zunehmende Bedeutung beigemessen.

Um politische Entscheidungsträger bei der Ausarbeitung solcher anspruchsvollen Werkzeuge zu unterstützen, strebt diese Dissertation an, ein besseres Verständnis dafür zu entwickeln wie Policy Mixes technologischen Wandel und organisationales Lernen im Energiesektor beeinflussen. Dazu werden in dieser Arbeit unterschiedliche Betrachtungswinkel miteinander kombiniert. Aufbauend auf bestehenden Erkenntnisse aus den Bereichen der Politikwissenschaft, der Innovationsstudien und Organisationstheorie, wird die Perspektive von politischen Akteuren, Firmen sowie Endkunden eingenommen.

Diese Arbeit basiert auf empirischen Daten aus dem Technologiebereich der „dezentralen Energieressourcen“ (DER), genauer gesagt um Energiesysteme im Wohnungssektor, die aus solaren Photovoltaik (PV) Anlagen und Energiespeichern bestehen. Diese Fallstudie wurde ausgewählt, da DER das Potenzial haben einen beispiellosen Wandel im Energiesektor auszulösen, der durch eine massive Verschiebung entlang der energiewirtschaftlichen Wertschöpfungskette in Richtung des Endkunden sowie erhebliche Auswirkungen auf bestehende und neue Marktteilnehmer gekennzeichnet ist. Das Zusammenwirken verschiedener Technologien, Anwendungen und Heterogenität zwischen Endkunden macht die Ausgestaltung von Politikmaßnahmen für DER besonders schwierig. Deshalb verspricht eine detaillierte Analyse des entsprechend Policy Mix sowie seiner Koevolution mit der DER Domäne wichtige Erkenntnisse für politische Entscheider und Analysten. Darüber trägt das sich ändernde Geschäftsumfeld dazu bei, dass etablierte Unternehmen ihre Strategie neu definieren und ihre Kernfähigkeiten anpassen. Diese Aspekte machen den DER Bereich zu einer wertvollen Fallstudie, um alternative Ansätze für organisationales Lernen zu beobachten und daraus neue Erkenntnisse für die Organisationstheorie abzuleiten.

Um das Zusammenspiel zwischen politischen Akteuren, Firmen und Endkunden in Bezug auf DER zu untersuchen, kombiniert diese Dissertation qualitative und quantitative Methoden, insbesondere Einzel- und vergleichende Fallstudien, sowie techno-ökonomische und agentenbasierte Modellierung. Dazu wird die übergreifende Forschungsfrage in vier Teilfragen zerlegt, wobei jede aus einer spezifischen Forschungslücke abgeleitet ist. Das erste Papier analysiert wie einzelne Gestaltungsmerkmale einer bestimmten Politikmaßnahme den Effekt eines übergreifenden Policy

Mixes beeinflussen. Die Mechanismen werden am Beispiel der Auswirkung auf die Wirtschaftlichkeit einer bestimmten DER Technologie eingehend untersucht. Das zweite Papier erforscht wie technologischer Wandel, insbesondere wenn durch Politikmaßnahmen eingeleitet, das Geschäftsumfeld von etablierten Unternehmen prägt. Dazu wird beleuchtet, welche Formen von organisationalem Lernen Unternehmen als Reaktion auf einen solchen Wandel wählen. Das dritte Papier untersucht zwei Ansätze zur Bestimmung der relevanten Elemente, aus denen ein gegebener Policy Mix aufgebaut ist. Das vierte Papier analysiert die Koevolution zwischen Policy Mixes, technologischer Diffusion und sektoralem Wandel, insbesondere bei gleichzeitigem Vorhandensein mehrerer politischer Zielsetzungen.

Diese Doktorarbeit beinhaltet vier spezifische Beiträge zur bestehenden Literatur. Erstens stellt die Arbeit einen analytischen Rahmen vor, der hilft künftige Forschungsbeiträge im Bereich Policy Mixes zu erleichtern. Dazu werden konkrete Handlungsempfehlungen gegeben, wie sich die Elemente eines zu analysierenden Policy Mixes abgrenzen lassen. Zweitens trägt diese Arbeit zur Policy Mix Literatur bei, indem sie Vorschläge macht, wie sich die Wirkung von multiplen Politikmaßnahmen sowohl im Nachhinein als auch vorab messen lässt. Drittens unterstreicht diese Dissertation die Rolle von Akteuren – allen voran politischen Entscheidungsträgern sowie Stakeholdern, die die technologischen Änderungen umsetzen – in der Entwicklung von Policy Mixes und ermöglicht dadurch einer differenzierteren Betrachtung der Herausforderung vertikaler und horizontaler Koordination von Politikmaßnahmen. Viertens adressiert diese Arbeit eine Fragestellung, die Wissenschaftler im Bereich der Organisationstheorie seit längerer Zeit beschäftigt, nämlich welche Merkmale im Unternehmensumfeld dazu führen, dass Organisationen einen bestimmten Ansatz wählen um ‚beidhändig' zu werden. Beidhändigkeit (Ambidextrie) im organisationalen Kontext bedeutet, dass ein Unternehmen es schafft, die zahlreichen internen Spannungen zu überwinden, die sich aus dem Gegensatz ergeben, bestehende Fähigkeiten und Ressourcen auszunutzen (Exploitation) und zeitgleich neue Geschäftsmöglichkeiten zu erkunden und zu entwickeln (Exploration). In diesem Zusammenhang stellt diese Doktorarbeit ein theoretisches Modell vor, das verdeutlich, dass die Reaktion etablierter Unternehmen auf Veränderungen ihres Geschäftsumfeldes von zwei konkreten Umfeld Faktoren wesentlich geprägt wird. Das neuartige Konzept „hybride Ambidextrie" hebt zudem hervor, dass Unternehmen die zuvor in der Literatur separat behandelten Ansätze der „strukturellen" und „kontextuellen" Ambidextrie kombinieren, sofern ihr Umfeld durch eine Vielzahl unsicherer Geschäftsmöglichkeiten geprägt ist, die zudem stark von ihren bisherigen Fähigkeiten und ihrer Kultur abweichen.

Auf der Basis dieser Beiträge, leitet die Arbeit einige Empfehlungen für Entscheidungsträger in Politik und Unternehmen, sowie für den Endkunden ab. Erstens, da bereits die Beurteilung der Auswirkung einzelner Politikmaßnahmen sehr aufwendig ist, gilt dies umso mehr für die Analyse von Policy Mixes, die aus einer Reihe von teils interagierenden Politikmaßnahmen bestehen und oft durch das zeitgleiche Verfolgen mehrerer Ziele geprägt sind. Daher legt diese Arbeit politischen Entscheidern, Analysten sowie Stabstellen der öffentlichen Verwaltung nahe ‚herkömmliche' politische Entscheidungsprozesse um Erkenntnisse aus systematischen, quantitativen Modellrechnungen zu ergänzen. Mögliche Ansätze werden innerhalb dieser Dissertation ausführlich vorgestellt. Zweitens, ohne eine klare Vision für die Rolle von dezentralen Energieressourcen (DER) in einem sich wandelnden Energiesystem, könnte eine beschleunigte Nachfrage nach diesen Technologien zu einem schrittweisen, zufälligen Einrasten (lock-in) in bestimmte sozio-technische Systeme führen, die sich vor dem Hintergrund der Energiewende langfristig als sub-optimal herausstellen. Daher sollten politische Entscheider eine „Prosumenten Strategie" entwickeln und ihre Politikmaßnahmen danach ausrichten, um das Gesamtpotenzial der DER Technologien für das Energiesystem und die Gesellschaft zu erschließen. Drittens, durch die große Anzahl und die Unsicherheit der Technologien im Bereich DER sollten Entscheidungsträger in der Politik Initiativen vorantreiben, die auf die Expertise und Mitbestimmung der Stakeholder setzen, die den technologischen Entwicklungen am nächsten sind und die deren Geschwindigkeit und Richtung entscheidend prägen bzw. davon beeinflusst werden. Viertens, Manager in Unternehmen können aus der Entwicklung der großen deutschen Energieversorger eine wichtige Erkenntnis ziehen, nämlich sorgfältig darauf zu achten, keine voreiligen Schlüsse aus einem sich ändernden Marktumfeld zu ziehen, insbesondere was die Entscheidung betrifft, neue Geschäftsmöglichkeiten auszuwählen bzw. zu ignorieren. Diesbezüglich unterstützt das im Rahmen dieser Arbeit entwickelte theoretische Modell zur organisationalen Ambidextrie Entscheider im Unternehmen bei der Analyse ihres sich wandelnden Geschäftsumfeldes und bietet zugleich eine Übersicht über mögliche Maßnahmen, auf diese Änderungen zu reagieren. Fünftens, der wachsende DER Markt konfrontiert Endkonsumenten mit einer Vielzahl neuer Technologien und Dienstleistungen. Endverbraucher sollten die verschiedenen Optionen daher sorgfältig abwägen, sich über politische Förderung informieren und sich bewusst machen, dass die Technologien durch einen unterschiedlichen Reifegrad gekennzeichnet sind. Wichtige Aspekte sind zum Beispiel die Kompatibilität zwischen Komponenten unterschiedlicher Hersteller, die Durchführbarkeit von Erweiterungen. Zudem gewinnt die zunehmende Auflösung der Grenzen zwischen dem Energie-, Gebäude- und Transportsektor an Bedeutung.

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1 Introduction

1.1 Mitigating climate change by decarbonizing the energy sector

Since 1988 the Intergovernmental Panel on Climate Change (IPCC) has collected and synthesized scientific evidence on climate change, assessing its severe, widespread and irreversible impacts[1] for people and ecosystems on this planet. Their assessments clearly reveal greenhouse gas (GHG) emissions caused by human activity as the fundamental driver of these developments (IPCC, 2014a). On April 22, 2016 – almost three decades, five IPCC reports, and 21 Conferences of the Parties (COP) later – leaders of the world assembled at the United Nation's headquarter in New York to sign the Paris Agreement. This landmark accord builds upon the United Nations Framework Convention on Climate Change (UNFCCC) and expresses the willingness of 195 countries to limit global warming to well below 2°C compared to pre-industrial levels (UNFCCC, 2015). However, in order to reach this goal, drastic measures need to be implemented in order to make the global community pivot from status quo to a sustainable pathway into the future.

Besides demand-side levers, such as behavioral change and increased energy efficiency, the IPCC has identified an increase in the share of low-carbon electricity supply from currently 30% to about 80% in 2050, and a phase-out of fossil fuels by 2100 as the two essential supply-side mitigation levers (IPCC, 2014b). Recent developments regarding this 'energy transition' provide reasons to be optimistic that humanity may engineer its way out of the climate change challenge. For example, since the 1990s wind power and solar photovoltaics (PV) have turned into an increasingly competitive alternative to GHG emission-intensive conventional power generation in both developed and emerging countries (IRENA, 2016a, 2015). As a result, in 2015 renewable energy sources (RES) represented the dominant share of newly installed power generation capacity around the world, with RES investments exceeding US$285 billion (UNEP/BNEF, 2016; WEF, 2016).

1.2 The role of policy mixes in escaping carbon lock-ins

The recent development in the RES domain can be regarded as an outcome of significant government interventions in the form of 'technology push' programs that spurred research, development and demonstration (RD&D) (Gallagher et al., 2011), as well as 'demand pull' policies that created niche markets and helped drive down costs through scale and learning effects (Hoppmann, 2015). Recognizing the decisive impact of public policy on global energy systems, the head of the International Energy Agency (IEA) recently concluded that "policies will determine where we go from here" (IEA, 2016; OECD/IEA, 2016). In fact, whether RES and other 'clean technologies' may actually build up the 'irreversible momentum' necessary for an effective decarbonization (Obama,

[1] Climate change impacts span across physical (e.g. melting glaciers, coastal erosion), biological (e.g. terrestrial and marine ecosytems), and human and managed systems (e.g. food production, livelihood).

2017) depends on overcoming the prevalent "technological, economic, social and institutional challenges[2]" in a timely manner (IPCC, 2014a, p. 20). Therefore, in order to transform the global energy system towards carbon-neutrality by the end of the 21st century, unprecedented policy reforms are necessary. These require moving away from policy 'patchwork', i.e. individual policy interventions designed to fix isolated issues, towards a more comprehensive 'transition management' that not only ensures that novel technologies make it to the market but that they eventually replace the existing fossil fuel infrastructure (Kivimaa and Kern, 2016).

In this respect, policy makers can draw on the insights gathered by scholars in various academic disciplines who have demystified the effect of policy on the development and diffusion of innovations in the energy sector (Fouquet, 2008; Gruebler et al., 1999; Jacobsson and Lauber, 2006). For example, recent innovation studies reveal that technology characteristics such as the complexity of the product architecture, the scale of the production process, and the applicability in different use cases significantly moderate the effect of policy on the innovation and diffusion process (Huenteler et al., 2016; Schmidt et al., 2016). Evolutionary and behavioral economics stress that technology adoption is the outcome of a boundedly rational decision process by heterogeneous actors who are affected by their social environment. This is especially relevant in light of the emerging role of energy consumers in terms of investments into RES for self-supply or changing energy service demands (Girod et al., 2017; Kairies et al., 2015). Important work at the boundary between political science and the innovation systems literature urges us not to apply an overly simplistic, static, and mechanistic understanding of policies, stressing the co-evolution between policy and technological change (Flanagan and Uyarra, 2016; Hoppmann et al., 2014a). Since it is impossible to integrate all of the former insights into a single, universally applicable policy instrument, recent work has started to assess so-called policy mixes, i.e. combinations of policies pursuing common strategic objectives, whose joint properties emerge from positive or negative interactions between the individual elements (Del Río and Howlett, 2013; Flanagan et al., 2011; Rogge and Reichardt, 2016).

In sum, there is a growing scientific basis for the design and administration of sophisticated[3] policy mixes that are geared towards spurring technological change and escaping 'carbon lock-in' (Unruh, 2002). While previous analyses yield invaluable insights for policy makers and firms shaping the energy sector, many aspects remain unclear. First, we currently lack methodology to consistently

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[2] Examples of these four issues are i) physical infrastructures designed around fossil fuels that render the energy, building, and transport sectors incompatible with high penetrations of intermittent RES (Arthur, 1989; Markard, 2011), ii) unpriced externalities that distort competition (Gallagher et al., 2011), iii) lack of acceptance of novel technologies (Negro et al., 2012), and iv) legal and regulatory structures that favor incumbent players deeply embedded into the predominant 'techno-institutional complex' (Unruh, 2000).

[3] Notwithstanding these analogies appear in the public debate, these approaches have little in common with the public policy programs for "atomic weapons and manned lunar landing" (Mowery et al., 2010, p. 1014) or a "high-tech version of a planned economy" (Mihm, 2016).

identify and systematically analyze the vertical[4] and horizontal[5] coordination issues within emerging policy mixes which can be regarded a prerequisite for better alignment of government agencies and policy instruments within and across jurisdictions (OECD/IEA/ITF/NEA, 2015). Second, while a lot can be learned from retrospective policy analyses, we know relatively little about the prospective consequences of alternative policy mix amendments on the diffusion of clean technologies and their systemic effects. Such analyses may provide actionable guidance to policy makers in charge of navigating the inherent complexity and uncertainty of energy technology innovation systems (Gallagher et al., 2012). Third, the fact that a quarter of the recent RES investment was allotted to small-scale, distributed generation that benefits from favorable demand-pull policies in a significant number of countries (Couture et al., 2015), is a sign that policy-induced technological change has the potential to significantly alter the role of incumbent firms and end consumers in the energy sector. However, our understanding about the underlying dynamics remains limited (Funkhouser et al., 2015; Grünewald et al., 2012; Mills et al., 2016; Richter, 2013). Given the need for climate change mitigation measures in many industries, insights about the antecedents, barriers, and mechanisms of actor-level change in the energy sector could provide valuable lessons for policy makers about how to increase the pace of adaptation of established players while promoting an active role for end consumers in sustainability transitions (Bergek et al., 2013; Lavie, 2006; Markard et al., 2012). So far, our limited understanding of how policies interact and jointly affect various stakeholders in the energy sector may delay or undermine the design of effective and efficient policy mixes geared towards escaping carbon lock-ins.

1.3 Research Framework

Given the increasingly important role of public policies in accelerating the energy transition as a central pillar of climate change mitigation, this dissertation aims at augmenting our understanding of *how policy mixes affect technological change and organizational learning in the energy sector*. To do so, the thesis adopts the perspective of three key stakeholders, namely policy makers, firms and end consumers, building on the insights from political science, innovation studies, and organizational theory (cf. Figure 1). To study the co-evolution between policy mixes, technological change, and organizational learning, this work combines qualitative and quantitative methodology to scrutinize the research case of technological change in the context of "Distributed Energy Resources" (DER). In addition to the above mentioned distributed RES, DER generally comprise energy generation, conversion, storage, and measurement & control technologies of small scale – hence connected to the distribution grid – that are typically located on residential, commercial, industrial or public premises – hence spatially dispersed – and often owned and operated by the customer. Evidence suggests that DER may fundamentally change the role of end consumers in the energy sector. For example

[4] Across governing levels.

[5] Across governing agencies.

investments into small-scale, distributed renewable generation have grown constantly in recent years and exceeded US$ 67 billion in 2015 (UNEP/BNEF, 2016).

Given that these developments are particularly salient in the residential sector of certain frontrunner countries, this dissertation draws on empirical data from California and Germany between 2000 and 2016. Both geographies have seen emerging multi-level, multi-goal policy mixes induce clean technology development and diffusion, yet they significantly differ in terms of their underlying energy sectors and policy approaches governing the energy transition.

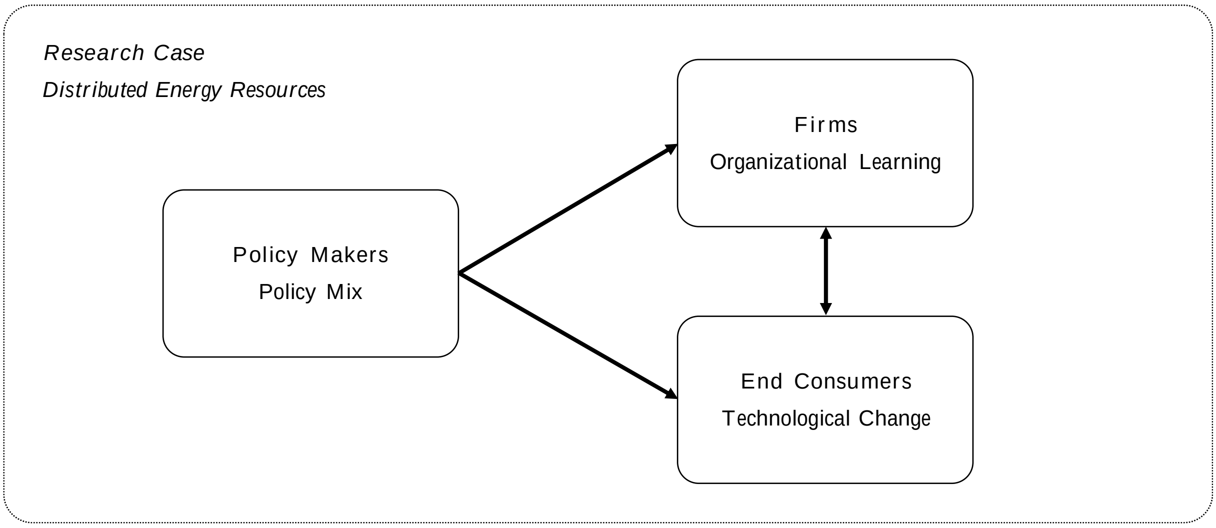

Figure 1: Simplified[6] Research Framework

This work focuses on residential solar PV and energy storage systems, narrowing down the scope of DER to further the analytical depth. Representing fundamentally different but highly complementary energy technologies, integrated residential "solar+storage" systems hold the potential to become a cornerstone of an emerging DER domain. This development is associated to a collapse of the traditional distinction between supply and demand in the energy sector, and could spur demand for renewable energy across sectoral boundaries (energy, building, transport). In sum, the research case presents a novel, increasingly important, yet insufficiently understood phenomenon in the energy sector that holds significant insights for theory and practice.

The remainder of this thesis is structured as follows: Chapter 2 introduces the relevant theoretical constructs and literature streams this dissertation is built on, and breaks down the overarching

[6] An extended version of the research framework is presented in Chapter 2.4 after the introduction of the theoretical constructs and the research objectives.

research question into four separate segments, each being based on a distinct gap in the literature. Chapters 3 and 4 outline the research design, including details on the research case and the selected methodological approaches. The main findings of the four research articles are provided in Chapter 5. Chapter 6 discusses the key contributions to the theoretical literature as well as the implications that arise for policy makers, corporate managers, and electricity customers.

2 Theory and Objectives

This chapter provides an overview of the most important constructs and conceptual frameworks this dissertation draws on (sections 2.1-2.3). For each literature stream, specific research gaps and problems are identified that provide the basis for the individual research questions of the four articles included in this dissertation (section 2.4).

2.1 Policy Mixes for Sustainability Transitions

Pressing societal challenges such as climate change or resource scarcity require timely reforms of legislation and regulation to be pursued in various sectors. Given the complexity of these socio-technical transitions, their effective governance requires a division of labor across legislators, regulators, and public administration according to competences or territorial imperatives (Ardrey, 1966). While this approach is well suited to leverage the expertise and capabilities across government agencies and governing levels, it may also lead to a fragmentation of policy making which results in policy instruments that fix isolated problems but may be misaligned with the overarching strategic objectives or undermine the effectiveness of policies in other fields. Policy science has been looking at these phenomena across a number of policy fields (Howlett and Lejano, 2012; Lindblom, 1979, 1959). However, only recently have researchers started to combine these insights with the literature on innovation and socio-technical transitions (Flanagan et al., 2011; Nill and Kemp, 2009; Smith et al., 2005). In a seminal article Rogge and Reichardt (2016) introduce a comprehensive framework for the analysis of "policy mixes" in the context of sustainability transitions (Markard et al., 2012). They conceptualize policy mixes as a composition of several interacting policy instruments that are embraced by an overarching policy strategy.

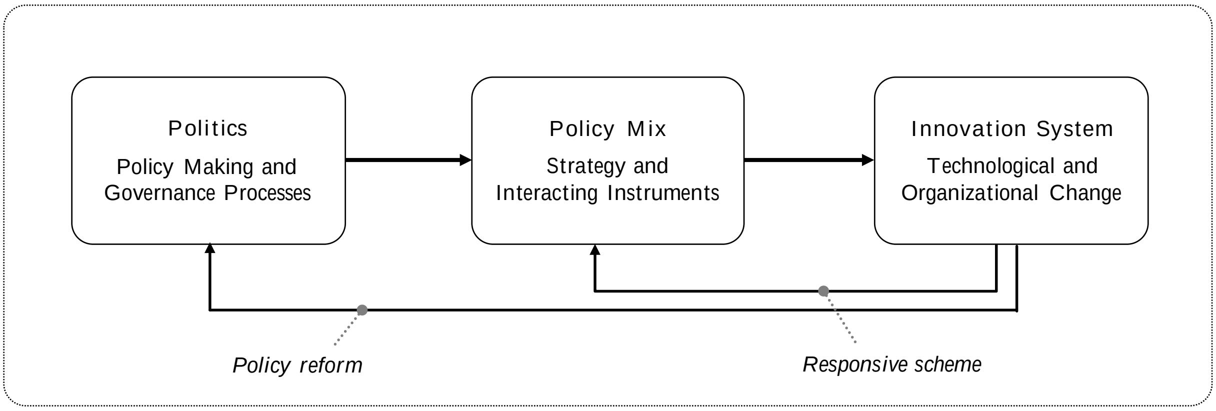

Figure 2: Illustration of the 'Policy Mix'
as an Output of Political Processes, and the Driver of Outcomes in the Innovation System

As illustrated in Figure 2, policy mixes are outputs of political processes and they co-evolve with their outcomes in the innovation system due to systemic feedbacks. These include substantial policy reforms – for example via "issues in the socio-technical system" that can set in motion sequences of compulsive policy-making (Hoppmann et al., 2014a, p. 1425) – or adaptation mechanisms within an existing policy mix – for example buy-down schemes (Duke, 2002). Real-world policy mixes often combine different types of instruments, pursue multiple goals, are frequently shaped by governing entities from different policy fields, and span multiple levels of public administration (Del Río and Howlett, 2013). Empirical analyses of policy mixes have been conducted in a number of different contexts (Del Río, 2010; Hoppmann et al., 2014a; Kern and Howlett, 2009; Reichardt et al., 2016; Spyridaki and Flamos, 2014).

However, despite these valuable insights into the core constructs and their relationships, the literature stream is still in its formation phase. Hence, several conceptual and methodological issues need to be ruled out before scholars can leverage the full potential of the policy mix framework. For example, it remains unclear how to delineate the relevant elements of a policy mix in a given setting, how to assess the impact of an evolving policy mix ex ante, and how to determine the success of a policy mix that pursues multiple strategic objectives. Without an answer to these fundamental questions, policy analysts may derive overly simplistic or unnecessarily complex representations of real-world policy mixes, resulting in inaccurate or extremely generic policy recommendations (Flanagan and Uyarra, 2016). Furthermore, the absence of an answer may inhibit the identification of important issues in the design of policy mixes, such as negative interactions between individual policy instruments that may undermine the effectiveness of the government intervention at large. Given the urgency of policy reforms in light of pressing sustainability challenges such as data privacy in the digital world, immigration restrictions or climate change, this thesis addresses several aspects of the research gaps outlined above, such as the issue of boundary setting and the lack of methodological clarity about policy mix assessments.

2.2 Energy Technology Innovation Systems

Emerging from industrial policy debates among European scholars in the 1980s, the concept of innovation systems gained traction as it explicitly recognized the systemic antecedents of technological change (Sharif, 2006). In particular, the literature has stressed the role of actors, networks, and institutions in collectively shaping the development of technological artifacts and determining the competitiveness of industries and national economies (Edquist et al., 1997). To augment our understanding of how policy mixes affect technological change and organizational learning in the energy sector, this dissertation draws on a recently proposed framework on "Energy Technology Innovation Systems" (ETIS) (Gallagher et al., 2012). This concept provides a comprehensive conceptual basis to explore the antecedents and barriers to the diffusion[7] of DER technologies, while taking the three focal stakeholder groups of this thesis into account.

Empirical studies conducted by technological historians and evolutionary economists have revealed that the key drivers for the large-scale adoption of novel technologies in the energy sector include the existence of cost reduction potential, early user-producer interaction, as well as mutually reinforcing effects between complementary technologies (both novel and existing ones) and their corresponding actors and institutions (Arthur, 1989; Gruebler et al., 1999; Mowery and Rosenberg, 1979). The latter 'network effect' is especially important since it "reduces the costs of technologies within the cluster, and increases the costs of incompatible ones" (Fouquet, 2008, p. 17). Historic examples of these positive externalities include *telephones and landlines*, or *oil extraction* and the *rise of the automobile*, while examples of promising emerging technology bundles are *intermittent renewables* and *energy storage*, as well as *electric vehicles* and *fast charging stations*.

When it comes to barriers that delay or prohibit the diffusion of novel technologies in the energy sector, typical examples include unpriced externalities that distort competition between clean and carbon-intensify technologies (Gillingham and Sweeney, 2012), knowledge spillovers that turn RD&D investments into high risk ventures (Jaffe et al., 2005), high discount rates for clean technologies (Waissbein et al., 2013), and technological as well as institutional 'lock-ins' that emerge from the mechanisms outlined beforehand (Unruh, 2000). To overcome these barriers, the creation of a niche market is of great importance since it provides premature, high cost technologies with a protected space that values their unique features and allows for learning and scale effects while shielding them from competition with mature, low-cost regime technologies (Malerba, 2009). This way, novel technologies avoid being regarded as substitutes for established technologies since they stress different product attributes and hence appeal to potentially different user segments. In the end, however, the new technology may be able to achieve the cost reductions and performance improvements necessary to compete with established technologies and pervade, and potentially replace them in their previously secure core market segments.

As a prerequisite to the former approach of market formation and diffusion, old and new technologies need to be sufficiently differentiable in terms of their value proposition. However, especially the supply side of the energy sector has been coined by its focus on commodities, i.e. fairly well substitutable energy carriers that restrict the potential for product differentiation while promoting actors to pursue cost competition. For example, despite the policy-induced formation of the RES market, many renewable technologies are not yet cost-competitive with conventional technologies (OECD/IEA, 2016). Given the need for a profound transition in the energy sector over the coming decades, it hence

[7] The ETIS framework depicts "market formation" and "diffusion" as the final stage of a "chain-linked" innovation process (Gallagher et al., 2012, p. 140). "Governments, firms, individuals" are seen as the key "innovation actors" (Gallagher et al., 2012, p. 143).

seems promising to assess DER as a demand side outcome of the ETIS. The reason is that DER are not advertised simply as an alternative form to e.g. generate electricity, since this market is already saturated by conventional technologies. Instead, providers of DER technologies are well aware that the adoption rationale of DER investors – typically residential and commercial end consumers – significantly differs from incumbent players such as electric utilities. More specifically, the uptake of the underlying technologies is driven more by soft factors such as hedonic motivation, social influence, and innovativeness, than by purely economic reasons (Girod et al., 2017; Kairies et al., 2015). For example, much like the chimney represented social status in medieval England (Dresbeck, 1971), a rooftop covered with solar PV panels may have a similar 'neighborhood effect' today. Since end consumers are heterogeneous in terms of their preferences, there seems to be ample potential for differentiated value propositions based on DER that could ultimately become the source of creative destruction in the energy sector (Bloomberg, 2016; Kivimaa and Kern, 2016).

Despite the far-reaching implications of DER diffusion for the entire energy system, e.g. the necessity of investments in the physical infrastructure[8], so far we lack robust estimates for the deployment of these systems in different scenarios. One of the reasons is that DER adoption, as outlined above, follows different rules than the incumbent technologies in the energy sector. Another reason (cf. previous section) is the strong impact of policy mixes on DER deployment, and vice versa. Therefore, this dissertation aims at achieving a better understanding of these phenomena, with a particular focus on the interplay between utility companies and end consumers.

2.3 Organizational Learning by Incumbent Utilities

As previously highlighted by the sustainability transitions and innovation systems literature, policy-induced technological change significantly transforms the business environment of actors in the energy sector, which particularly affects the role of established firms such as electric utility companies. Whereas the innovation systems literature studies these phenomena on an industry level (Bergek et al., 2013), scholars in the field of organizational theory and management science adopt the perspective of the firm and their respective decision makers. Firm-level studies are particularly useful to shed light on the intra-organizational dynamics and mechanisms and hence lend themselves to a detailed analysis of how policy-induced technological change transforms incumbent organizations and vice versa. This is particularly relevant since incumbent firms, especially in infrastructure sectors, are strongly intertwined with the formal and informal institutions. Hence, as long as they maintain their predominant role, their firm strategy has profound implications for socio-technical change in their industry.

[8] Such as investments into the transmission and distribution (T&D) infrastructure (consisting of overhead lines, transformers, and switchgear) or into conventional peaker plants based on gas turbines.

In this regard, several streams in the literature have elaborated on how incumbent organizations perceive and react to changes in their environment, in particular scholars who study organizational learning, ambidexterity[9], capabilities and cognition (Eggers and Kaplan, 2013; Hodgkinson and Healey, 2008; Levinthal and March, 1993; O'Reilly and Tushman, 2013; Tripsas and Gavetti, 2000). In his seminal article, Jim March (1991) builds on the distinction between "exploration" and "exploitation", and studies the relationship between these two learning modes as part of the adaptive processes that unfold in organizations. The process of exploration relates to 'search, experimentation, play, and flexibility', whereas exploitation refers to 'choice, execution, refinement, and efficiency'. Each builds on and reinforces particular skills, knowledge, resources, and organizational designs. It follows that successful firms are "ambidextrous" since they manage to balance the two learning modes despite the tensions and trade-offs that can be observed on multiple levels of the organization (Lavie et al., 2010, p. 112). Shifting from exploitation to exploration is particularly difficult "in the presence of fit" between the organizational capabilities and the business environment (Siggelkow, 2001). The reason is that capabilities, especially those in the "core" that coin competitive advantage and firm performance for a long period of time, turn into rigidities and hence inhibit organizational change (Leonard-Barton, 1992; Patel and Pavitt, 2000). In the words of Mary Tripsas (2009, p. 441) "[e]xisting capabilities, resource commitments, behavioral routines, and cognitive frames frequently constrain a firm's response to external change such that the same elements that helped foster success under one technological regime become inertial forces, limiting adaptive flexibility and driving suboptimal outcomes in a different environment". Hence, overcoming these constraints and reconfiguring capabilities becomes vital for firm survival in times of transformations in the organizational environment (Lavie, 2006; Tripsas, 1997). However, several factors render this challenge particularly salient in incumbent utilities. For example, as a result of regulation and specialization in the energy sector, the technological innovation process has become highly supplier-dominated (Pavitt, 1984, p. 353f). As a result, most of the explicit and tacit knowledge in terms of developing and manufacturing power generation equipment resides outside of utility companies, namely in technology providers (Markard, 2011, p. 114).

Recognizing these particularities and the policy-induced nature of socio-technical change in the energy sector, a number of empirical analyses have described important aspects that moderate the reaction of incumbent utilities to environmental change. These include regulatory interventions creating capability gaps (Worch et al., 2013), the confluence of technological change and shifting consumer preferences (Richter, 2013), and the ability to alter the pace and direction of change in the business environment via corporate political action (Stenzel and Frenzel, 2008). However, most of these analyses study organizational change at an industry level, rather than zooming into the individual firm or observing adaptation at the individual or group level. Understanding the intra-organizational mechanisms behind these phenomena could help overcome the lock-ins faced by incumbents firms in

[9] The ability to use both hands equally well.

the energy industry and hold valuable insights for related industries facing fundamental changes to their organizational environment (automobile, banking). This could ultimately enable established firms in the energy sector to turn from opponents to agents of change which may address many of the predominant "technological, economic, social and institutional challenges" simultaneously (IPCC, 2014a, p. 20; Jiang et al., 2010).

2.4 Summary of Objectives

This dissertation elaborates on four distinct gaps that have been identified in the literature streams outlined above. Due to their central role in shaping the energy transition in terms of DER diffusion, the first three papers sequentially adopt the perspective of each of the three focal actors – the end consumer, the firm, and the policy maker (cf. Table 1).

Table 1: Overview of the Papers included in this Dissertation

#	Perspective	Title	Research Question
I	End consumer	How feed-in remuneration design shapes residential PV prosumer paradigms	How do the key elements in feed-in remuneration design affect the investment rationale of residential prosumers?
II	Firm	Hybrid ambidexterity: how the environment shapes incumbents' use of structural and contextual approaches	How does the organizational environment shape a firm's use of structural and contextual ambidexterity?
III	Policy maker	Delineating policy mixes – contrasting the top down and bottom up approach along the case of energy storage in California	How do the two archetypical approaches to delineate a policy mix – top down vs bottom up – affect its scope and subsequent analysis?
IV	Policy maker End consumer Firm	How policy shapes the diffusion of residential solar+storage systems – An agent-based simulation of California's energy transition	How do the three most relevant policy instruments affect the diffusion of residential solar PV and battery systems in California between 2005 and 2030?

The first paper scrutinizes the economics of one of the key technologies in the DER domain, namely residential solar PV systems. In particular, it investigates how the design features of a specific policy instrument, namely feed-in remuneration, affect the sizing of residential PV systems and thereby ultimately shape the role of prosumers[10] in the electricity sector. The second paper studies the initiatives that incumbent utilities launch in response to the energy transition, in particular to the uptake of renewable energy technologies and the downstream shift of business activities. The goal is to derive a widely applicable, theoretical framework that maps alternative approaches to achieve

[10] Consumers who self-supply a certain portion of their demand.

organizational ambidexterity to the characteristics of changing business environments. The third paper identifies and elaborates on different methodological approaches to delineate and operationalize policy mixes. In the absence of clear rules and guidelines for boundary setting, policy mix analyses may produce inconsistent findings, which may undermine the value of this novel theoretical framework. This may prohibit scholars from using it to comprehensively study the policy interventions that drive sustainability transitions, and provide actionable recommendations for their improvement in light of the enormous complexity of governing emerging technology domains such as DER. Paper IV elaborates on the system-level interplay of all three actors, aggregating the insights from the three former articles. In particular, it looks at how a specific policy mix affects, and is affected by, the diffusion of a particular DER, namely residential solar+storage systems. The aim is to propose a method on how to assess such a complex co-evolutionary process ex ante, providing insights into the effectiveness and efficiency of policy interventions on multiple dimensions.

In sum, assessing the DER phenomenon from different, complementary perspectives yields important practical implications for decision makers in public policy and corporations, as well as residential energy consumers. Moreover, the research case provides a rich basis for inductive theory building, deriving important insights for the literature on policy mixes and organizational learning. Figure 3 presents an updated outline of the overarching research framework of this dissertation indicating which mechanisms are studied in each of the four articles.

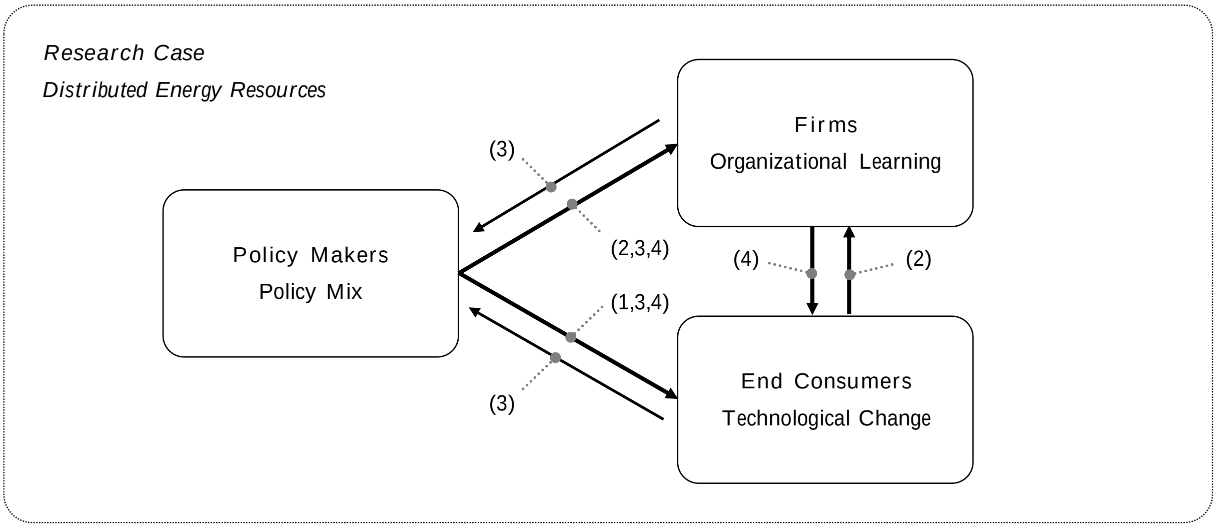

Figure 3: Extended Research Framework

3 Distributed Energy Resources (DER)

3.1 Definition and Taxonomy

Despite the absence of a widely agreed definition, a review of the literature reveals that Distributed Energy Resources (DER) are usually described as a domain that comprises energy generation, conversion, storage, and measurement & control technologies of small scale (hence connected to the distribution grid) that are typically located on residential, commercial, industrial or public premises (hence spatially dispersed) and often owned and operated by end consumers. While the definition may appear similar to the term "smart grid", it deliberately excludes the distribution grid and thus allows for a clear separation of behind-the-meter and front-of-meter assets.

The notion of DERs has been coined in the field of electrical engineering in the 1990s, and initially referred to micro generation, and combined heat and power units co-located with commercial and industrial demand. Together with the uptake of distributed solar PV, small-scale wind, biogas, and biomass in the 2000s, the meaning of the term shifted implicitly with respect to its generation component, namely from fossil fuels to renewables sources (El-Khattam and Salama, 2004). At the same time, the technological focus shifted from distributed generation (Ackermann et al., 2001) to demand response (DR) and demand side management (DSM) (Carley, 2012). Recently the term has expanded to include smart measurement and control devices as well as energy storage technologies such as vehicle-to-grid (V2G) systems (Atzeni et al., 2013; Deign, 2016). A taxonomy of the underlying technologies is provided in Table 2.

Table 2: A Taxonomy of Distributed Energy Resources

Distributed...	Generation	Conversion	Storage	Measurement & Control
Exemplary technologies	• Solar PV • Solar thermal • Micro wind • Gas boiler • Diesel generator	• End-use appliances (lighting; cooking; washing; ICT) • Heat pump • Immersion heater	• Stationary batteries • V2G • Heat storage • Cold storage • Building hull	• Smart meters • DR/DSM • Smart thermostats • Remote control • Aggregation
System-level implications	From consumer to prosumer	From standard load to flexible demand	From load defection to grid defection	From on/off to real-time flexibility

Based on bibliometric analysis of 1,163 articles* retrieved from 'Web of Science', building on a search string for DER using a similar approach to Woon et al. (2011) (*A total of 2,349 elements were retrieved; entries without DOI were removed)

The evolution of DER in terms of the technologies comprised is tied to both a paradigm shift in the role of the end consumer and a value shift in the energy system that is known as "new downstream"

(McKinsey&Company, 2014). With regard to the potential aggregation of thousands or millions of DER assets into virtual power plants, practitioners have envisioned the uptake of DER as the beginning of an "internet of electricity" (Newcomb and Paulos, 2013) and hope that the currently intricate interconnection procedures could be replaced by standardized, transparent, and automated processes resembling "plug-and-play" solutions (Klemun, 2013, p. 7). As a result, the traditional boundaries between value chain steps in the electricity sector do not exist any longer and the notion of unidirectional power flows and a hierarchical, centralized infrastructure seem increasingly outdated. In light of the profound changes for grid planning, investments, operation, maintenance and regulation (Borenstein, 2015; Kind, 2013), a surge of studies informs utilities, grid providers, utility regulators, and policy makers about the system-level impact of DER, e.g. (Akorede et al., 2010; Corneli et al., 2015; Desrosiers, 2014; DNV GL Energy, 2014; Kind, 2013; Mills et al., 2016; NARUC, 2016; Newcomb et al., 2013; SolarCity, 2016; Stanfield and Vanega, 2015). However, while these analyses offer rich insights for decision makers in their corresponding empirical setting, few studies elaborate on generalizable conceptual frameworks that support policy makers and corporate managers across contexts.

3.2 Rationale behind Case Selection

Given the aim of this dissertation to develop rather than testing theory, a theoretical sampling approach is chosen. "Theoretical sampling simply means that cases are selected because they are particularly suitable for illuminating and extending relationships and logic among constructs" (Eisenhardt and Graebner, 2007, p. 27). In this regard, the research case of DER is particularly well suited to study *how policy mixes affect technological change and organizational learning in the energy sector* for the following four reasons.

First, as outlined above, DER represents a large array of technologies (hardware and software) which significantly differ in terms of their individual characteristics. As we know from prior research, these technology characteristics, such as the complexity of the underlying product architecture, may strongly moderate the effect of policy on their development and diffusion (Huenteler et al., 2016). As a result, assessing the impact of policy on various competing DER technologies at different stages in their lifecycle is a challenging task. *Second*, the DER domain is not only coined by various technologies but also by a large number of applications that these technologies are able to address. Previous studies have shown that the intensity and the structure of competition between technologies may strongly differ from application to application (Battke and Schmidt, 2015; Schmidt et al., 2016). Hence, applications play a strong role in determining winners and losers among technologies. This suggests that policy design should recognize this attribute e.g. when it comes to reducing the public cost of demand-pull policies spurring technology deployment in the DER domain. *Third*, many DER technologies are currently incompatible with the existing physical infrastructure in the energy sector. Therefore, in case of a strong uptake of DER a transformation of the entire system becomes a prerequisite to accommodate e.g. solar PV penetrations beyond a certain threshold. Such a profound, high cost, system-level change requires a sophisticated governance approach involving a high level of inter-agency cooperation and coordination (Carl et al., 2012; Grueneich and Carl, 2012). Hence studying these internal dynamics of policy mixes could hold valuable implications for decision makers governing energy transitions in different jurisdictions. *Fourth*, as outlined beforehand, the adoption of DER is consumer driven. This means that the successful diffusion of DER from niche to mass markets depends on the preferences and 'distributed decision-making' processes of boundedly rational individuals (St John, 2015). In other words, the DER domain carries the potential for an unprecedented downstream shift of value in the energy sector, which has strong implications for governance of sectoral change as well as incumbents and new entrants trying to develop new business models based on DER.

In sum, policy design for DER is a very challenging task. This is why a thorough assessment of the corresponding policy mix and its co-evolution with the DER domain may yield important insights for policy makers and analysts. Moreover, the emergence of DER confronts decision makers in firms with a complex situation due to the confluence of at least three important developments: i) a changing policy and regulatory landscape; ii) rapidly changing technologies with short innovation cycles; iii) a paradigm change at the grid edge where a consumer base that has been loyal and modest for a century gradually turns into prosumers. As the changing business environment requires incumbent firms to redefine their strategy and adapt their core capabilities, it provides a valuable case to observe and derive insights into alternative organizational learning approaches.

3.3 The emerging Residential Solar+Storage Domain

Given that a holistic assessment of the interplay between policy, firms and end consumers in the context of DER is beyond the scope of this dissertation, the research case is narrowed down to a specific technology bundle and consumer segment. In particular, this work focuses on residential solar PV and energy storage systems that were first sketched in the 1980s and have been substantially developed since then (De Mey and Simoens, 1981; Guccione, 2017; Landgrebe and Donley, 1983). Due to the uptake in manufacturing capacity and market size, and the corresponding cost decreases over the last decade, distributed solar PV has become the single most important technological driver of the DER domain. Furthermore, distributed energy storage systems, such as battery storage and thermal energy storage systems, are regarded as an ideal complement to PV as their combination yields a more reliable, less intermittent energy generation unit. Based on the different energy storage technologies that are available[11] various types of 'decentralized energy units' can be envisioned. In this way, the electric energy that is generated by residential solar PV systems may be converted into other forms of energy, thereby addressing multiple applications[12] and end-uses across energy carriers.

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[11] For instance, battery storage, hot and warm water reservoirs, or ice storage attached to heating, ventilating, and air-conditioning (HVAC) units.

[12] Depending on their cell chemistry and power-to-energy ratio, battery systems allow end consumers to increase the share of onsite consumption of PV electricity, achieve electricity bill savings through tariff

However, tension arises from the fact that the investment rationale and the operation mode of these systems located behind-the-meter (BTM) may be in conflict with the in-front-of-the-meter (FOM) infrastructure and hence with the interest of society. For example, studies clearly point out that "the positive grid impact of such battery systems highly depends on the underlying economic and regulatory frameworks" (Von Appen et al., 2015, p. 618). Framed as building blocks of a decentralized energy system, distributed PV and energy storage systems could entail a 'distributed disruption' with significant implications for the existing infrastructure and established players in the sector (Burger and Weinmann, 2013; Mills et al., 2016). Studying these phenomena is particularly relevant in the residential sector since residential end consumers represent the largest group of potential DER adopters, are characterized by significant heterogeneity in terms of preferences and characteristics, and may significantly contribute to carbon reduction[13] (Kwac et al., 2014). While the former two attributes render the future diffusion of residential solar+storage systems hard to estimate, a systematic assessment could augment the understanding of several stakeholders in terms of policy design and organizational adaptation.

3.4 The Context of California and Germany

As a basis for the collection of empirical data, California and Germany have been selected as the two focal geographies. Representing two of the largest economies in the world (California[14] 6th and (Germany[15] 4th largest GDP in 2015), the two states have the potential to drive the global energy transition and provide templates for how to reduce per capita emissions while maintaining prosperity and high standards of living. In particular, both California and Germany are already regional frontrunners in terms of their transition goals and policy mixes. The same holds true for the emerging ETIS with technology providers that hold leading positions in the industries for battery storage systems, electric vehicles, and software design (California), or solar PV and wind turbines, transmission and distribution systems respectively (Germany). Finally, as illustrated in Figure 4 California and Germany are home to the largest solar PV markets in their region, which holds true across all market segments, i.e. from 'utility-scale' to 'residential'. While the market for combined solar+storage systems is still in its infancy – with about 500-1,000 systems installed in California (CSE, 2017; Wesoff, 2016) and about 40,000 systems installed in Germany (Badeda et al., 2017, p. 16) – both geographies can still be considered 'hotbeds' for residential solar+storage systems with ample potential for future market development. Apart from the former similarities, California and Germany differ in several aspects, which is fruitful when it comes to conducting comparative

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arbitrage, or replace conventional backup generators such as diesel engines (Battke et al., 2013; Crabtree, 2015; Fairley, 2015; Kempener and Borden, 2015; Lee et al., 2015). Due to their versatility, some denote batteries as the "Swiss Army knife of the grid" (Beney and Wesoff, 2015).

[13] "Globally, around 30% of electricity consumption is by residential users" (IRENA, 2016b, p. 39)

[14] Based on 2015 US state-level GDP data from (BEA, 2017).

[15] Based on 2015 global GDP data from (WorldBank, 2017).

assessments. For example, the two regions are coined by considerable differences in their energy transition policy mixes, especially when it comes to the interventions that affect the emerging DER domain. Part of that can be traced back to their integration into the overarching US federal level (e.g. the 'Clean Power Plan'), respectively European Union (e.g. the 'Energy Union') policy contexts.

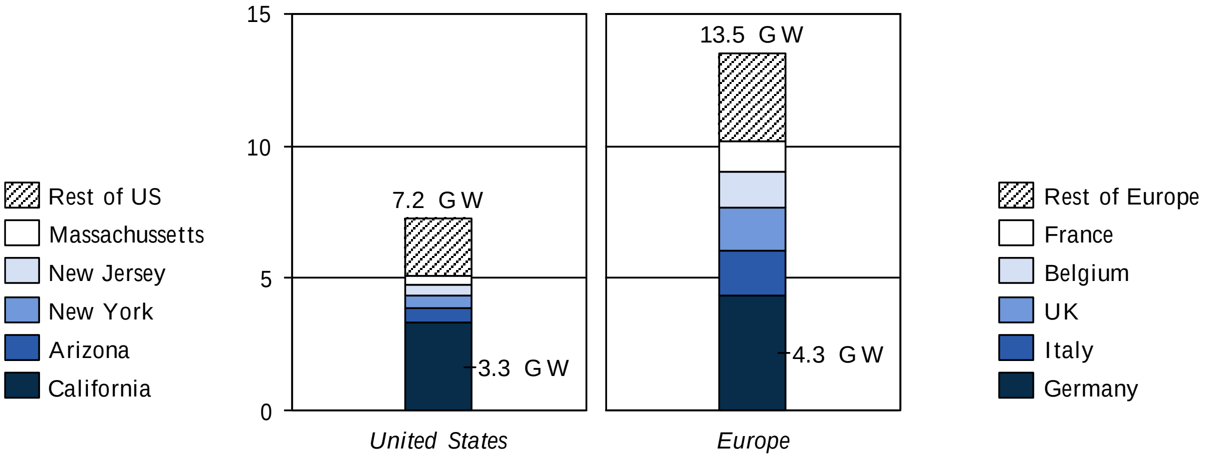

Figure 4: Residential Solar PV Capacity installed by the End of Year 2015
US Data from (EIA/DOE, 2016); European Data from (EPIA, 2016)

Moreover, the retail electricity markets in the two states vary substantially. In particular, residential customers in California are served by regulated monopolies, while end consumers in Germany have the freedom to choose their electricity provider as part of a liberalized, and since the late 2000s also competitive retail market. Furthermore, electric utilities in Germany were among the first to see fundamental changes to their business environment and launched profound organizational change processes. But whereas Germany's DER market has recently shrunk in terms of annual installed capacity[16], California's market grows continuously. Due to the high solar irradiance in California, this uptake is likely to entail much more disruptive[17] system-level consequences than in Germany.

In sum, California and Germany are widely regarded frontrunners when it comes to the development and system integration of DER technologies, but exhibit differences in several attributes. Therefore, studying these two cases is expected to yield important insights for policy makers and corporate managers in jurisdictions with an increasing share of DER.

[16] The annual market share of small-scale solar PV installations smaller than 40kW (typically reflecting adoption by residential and small commercial customers) has dropped from about 75% in 2004 to 30% in 2015 (EPIA, 2016).

[17] Cf. the 'duck curve' debate (CAISO, 2016)

4 Method and Data

As outlined in the previous chapter, several technological and socio-economic features render "Distributed Energy Resources" particular to study. In order to capture different aspects of this research case and fully explore what they imply for theory and practice, this dissertation applies a mix of both qualitative and quantitative methodology (Creswell, 2009). The following sections outline the rationale behind each of the three selected methods, as well as the three major sources of data that are drawn on to arrive at the findings in Chapter 5.

4.1 Methods

Case Study

As stated in Kathleen Eisenhardt's (1989) seminal article, case study research is well suited for the analysis of phenomena for which little theory exists. In particular, it allows researchers to gain an in-depth understanding of the focal research case, while capturing the richness of its context. This is done by drawing on and connecting a wide array of data sources such as annual reports, press articles, videos and personal interviews (Weick, 2007). Based on this thorough understanding, the insights gained from case studies lend themselves as a basis for inductive theory building (Yin, 2009).

While a single-case study design is usually employed to describe a novel phenomenon for the first time and bring its existence to the attention of a wider audience (Siggelkow, 2007), a multi-case study allows for a comparative setup. The latter helps clarify "whether an emergent finding is simply idiosyncratic to a single case or consistently replicated" and hence usually provides "better grounded, more accurate, and more generalizable" theory (Eisenhardt and Graebner, 2007, p. 27). The latter aspect is especially important concerning the general downside of case study methodology, namely questionable external validity in case the findings are contingent upon the specific context. To mitigate this issue, the emerging theoretical contributions of this dissertation were discussed with several representatives with different professional backgrounds and industry affiliations. They suggest that many of the findings presented in Chapter 5, and discussed in Chapter 6 may be applied beyond their focal context and, in part, even beyond the energy sector.

This dissertation draws on both single and multiple case study design, depending on the degree of novelty of the focal phenomenon under scrutiny. In particular, Papers III and IV conduct single-case studies to independently identify and analyze two specific policy mixes in California. By contrast, Papers I and II employ multi-case studies to contrast the design features of a selected policy instrument between California and Germany, and to scrutinize alternative ambidexterity approaches in Germany's utility industry respectively.

Techno-Economic Modelling

Techno-economic modelling allows researchers to systematically assess the economics of a given technology, while taking a large number of technical and economic input factors into account. In contrast to the real world, the artificial modelling environment can be used to conduct 'all-else-equal' analyses and thus isolate, explore and quantify the impact of each individual input variable (e.g. natural environment; technical parameters; economic inputs). In many cases, the development of the model is as valuable as the subsequent analyses that build on it. The reason is that proper techno-economic models find the right balance between comprehensively depicting all of the important mechanisms, while remaining comprehensibility in terms of interpreting the key outputs (Khatib et al., 2012; Lang et al., 2016). The possibility to choose from a range of output metrics, programming approaches, and computational environments renders the approach very flexible, which is one of the key reasons for its wide application throughout the literature, e.g. (Christoforidis et al., 2016; Comello and Reichelstein, 2016; Poullikkas, 2013; Stephan et al., 2016). In order to assess the robustness of the findings of the focal analyses, techno-economic models can be used to run sensitivity analyses, scenario analyses, or Monte-Carlo simulations depending on the nature of the input variables (Battke et al., 2013; Hoppmann et al., 2014b)

This dissertation makes use of techno-economic modelling to shed light on the economics of DER technologies from the perspective of a residential household. Based on a building simulation tool that can be used to derive synthetic energy supply and demand profiles for every geo-location around the world (Lang et al., 2016, 2015, 2013), Paper I and Paper III elaborate on investments into stand-alone rooftop solar PV, and combined solar+storage systems respectively. The economic attractiveness is operationalized as the net present value (NPV) of the corresponding investments. This metric is chosen since it includes both the cost and the revenue side of the investment, allows for the comparison between energy technologies with different lifetimes and characteristics, and captures the time value of money by incorporating a discount factor.

Agent-Based Modelling

While the diffusion of a novel technology may be strongly affected by its economics, additional aspects such as individual attributes and behavior play a major role (Gunderson and Holling, 2002). As a consequence, technology adoption is driven by boundedly rational consumers who interact with, learn from and adapt to their socio-technical environment (Miller and Page, 2007). Agent-based models (ABM), which have been applied in a range of disciplines, can be used to depict these features and study the evolution of complex socio-technical systems. This seems especially relevant for the analysis of system-level phenomena in the energy system which should be based on "methods which recognize the complexity of energy systems in relation to social, technological, economic and environmental aspects" (Bale et al., 2015, p. 150). Paper IV develops an agent-based model to quantify and elaborate on how alternative designs of policy mixes affect and are affected by the diffusion of residential solar PV and battery systems. In addition, the model is used to evaluate three important system-level indicators (market development, grid impact, cross subsidization) and provide guidance for the governance of California's energy transition in terms of the state's overarching policy goals.

4.2 Data Sources

Interview Data

The collection of primary data is well suited to capture a novel phenomenon in great detail. In particular, "[i]nterviews are a highly efficient way to gather rich, empirical data, especially when the phenomenon of interest is highly episodic and in-frequent" (Eisenhardt and Graebner, 2007, p. 28).

Since Papers II and III intend to derive actionable recommendations for organizational adaptation and policy mix design respectively, this dissertation draws on an extensive set of interviews to gain a thorough understanding of the emerging DER phenomenon, which was still in its infancy during the time of this study. Incorporating data from 68 formal, semi-structured interviews with policy makers, corporate executives, and academics in California and Germany, it was possible to subsequently disentangle the underlying mechanisms and gain insights into the major decision making processes in the public and private sector. The majority of these interviews were recorded, transcribed, and later coded by the research team. Triangulation between different interviewees was used to avoid being biased by the perspectives, normative assertions and cognitive frames of individuals. While the early interviews contained many open questions to explore the constructs and mechanisms, interviews in the later stage of the project shifted to closed questions to see whether the latest research framework was regarded accurate or spurred objection. In addition, the emergent findings were frequently discussed in a series of informal interviews with experts from the energy sector as well as from the banking and manufacturing industries, partly during five conference visits at different stages in the investigation period.

Archival Data and Techno-Economic Inputs

The collection of archival data is useful to shed light on a phenomenon for which primary data is difficult to gather, either because researchers lack access to it, or because the time period of interest is in the past. Secondary data may comprise both qualitative and quantitative data (e.g. press articles, books, patents, rulemakings, audio or video recordings, manuals, technical sheets, or statistics) that can be retrieved from a wide variety of sources (e.g. newspapers, corporations, government agencies). Triangulating between different types and sources of data allows researchers to adopt different views on the focal phenomenon and gain a robust understanding of it without having to be on site.

Since a considerable share of this dissertation is based on longitudinal case studies, an extensive body of archival data documents were collected and systematically analyzed to gain a thorough understanding of the evolution of the residential solar+storage domain. In addition, social (e.g. customer demographics), technical (e.g. degradation), environmental (e.g. irradiation), micro-economic (e.g. system costs), and market (e.g. installed capacity) data was collected for the investigation time frame and used as input parameters for the corresponding modelling models.

4.3 Overview

Table 2 summarizes[18] the methods and data sources employed by the papers contained in this dissertation. While all of the articles are based on single or comparative case studies, the two quantitative approaches introduced in section 4.1 are used by a subset of the papers.

Table 3: Methods and Data Sources used in Papers I-IV

#	Research Question	Goal	Method	Data Sources	Scope	
I	How do the key elements in FiR design, i.e. remuneration levels and feed-in constraints, affect the investment rationale of residential prosumers?	Policy analysis (ex post)	Case study (multiple) & Techno-economic model	Archival data on residential solar PV policies, revenues, costs, and deployment retrieved from governing agencies and research institutes in both geographies	CA [1] DE [2]	2005-2016
II	How does the organizational environment shape a firm's use of structural and contextual ambidexterity?	Theory building	Case study (multiple)	Archival data on Germany's four incumbent electric utilities from corporate websites and press articles (12,868 documents) Notes and transcripts of 44 interviews with corporate managers and industry experts	DE	2005-2016
III	How do the two archetypical approaches to delineate a policy mix, top down vs bottom up, affect its scope and subsequent analysis?	Method developm. & Theory building	Case study (single) & Techno-economic model	Archival data on 66 energy storage policies retrieved from governing agencies and press articles (~300 documents) Notes of 24 interviews with policy makers, and industry experts	CA	2005-2016
IV	How do the three most relevant policy instruments affect the diffusion of residential solar PV and battery systems in California between 2005 and 2030?	Policy analysis (ex ante)	Case study (single) & Agent-based model	Archival data from Paper II for different energy service territories in California Longitudinal data on residential battery policies, revenues, costs, and deployment retrieved from governing agencies and research institutes	CA	2005-2030

[1] California; [2] Germany

[18] Details on the analytical process for each of the four articles are provided in Annex I.

5 Summary of Results

This Chapter summarizes[19] the main findings of the four papers included in this dissertation. Due to their distinct objectives and self-standing research designs, the results for each study are presented in separate sections. They serve as the basis for the theoretical contributions and practical implications outlined in Chapter 6.

5.1 Paper I: How Feed-in Remuneration Design shapes Residential PV Prosumer Paradigms

The economics of residential solar PV systems in most countries are essentially determined by the upfront costs for installing the system, the revenues that can be expected from avoiding to buy electricity from the electricity provider, and for feeding electricity into the grid at times when production exceeds onsite consumption. All three of these aspects can be affected by policy instruments. Upfront grants and tax credits may lower investment costs (cf. Figure 5: *Effect 1*); consumption taxes, levies, and regulation of electricity tariffs can alter the level of bill savings (cf. Figure 5: *Effect 2*); and feed-in remuneration (FiR) design makes electricity generation for the grid more or less attractive (cf. Figure 5: *Effect 3*). In light of strong cost decreases of solar PV in recent years, and the challenges associated to integrating high penetrations of solar PV in the electric grid, a contested debate revolves around the future of these PV support schemes. Given its central role in the discussions, this study looks at how the design features of feed-in remuneration policies affect the investment rationale of residential prosumers.

The study holds three particular insights. *First*, feed-in remuneration design provides policy makers with a number of flexible levers to affect the deployment of residential solar PV systems. In particular, based on an economic and a regulatory component, policy makers can steer the remuneration level[20] and set feed-in contraints[21]. *Second*, the former design features not only affect the profitability of a given residential solar installation, but consequently impact the optimal size of the systems that are being deployed. As a consequence, depending on the going FiR design, investors may decide not to invest into solar PV at all, dimension their installation for a specific level of self-consumption, or entirely for grid production, with various shades of grey in between. To elaborate on the underlying mechanisms, the study develops a techno-economic model and a framework to illustrate the policy drivers behind residential solar PV paradigms. Since the calculations are based on relative, not absolute, metrics, the toolset can be applied to various empirical contexts and intuitively shows how FiR design in confluence with upfront support and rate design affects the economics and rationale of

[19] Detailed results are presented in Annex I.
[20] For example: based on exogenous value or tied to retail or wholesale market; fix vs volatile
[21] For example: based on installation size, instantaneous (power) or cumulative feed-in (energy)

a residential solar PV investor. *Third*, the applicability of the framework is demonstrated for the cases of California and Germany, given their significant difference in policy design. As revealed by the two trajectories in Figure 5, the reason for the deployment of significantly larger residential PV systems in Germany, compared to California, can be traced back to differences in the two corresponding FiR policies, namely the Feed-in Tariff (FIT) and the Net Energy Metering (NEM) scheme. While the shift along the vertical axis happens due to growing prices for retail electricity, and simultaneously falling net investment costs for residential PV systems (upward trend), the separate developments along the horizontal axis (increase followed by a decrease in Germany; stark increase in California) are caused by the going FiR design. These findings stress the importance of seemingly minor features of individual policy instruments for the development of the energy transition at large, which entails valuable lessons for designing future policy mixes.

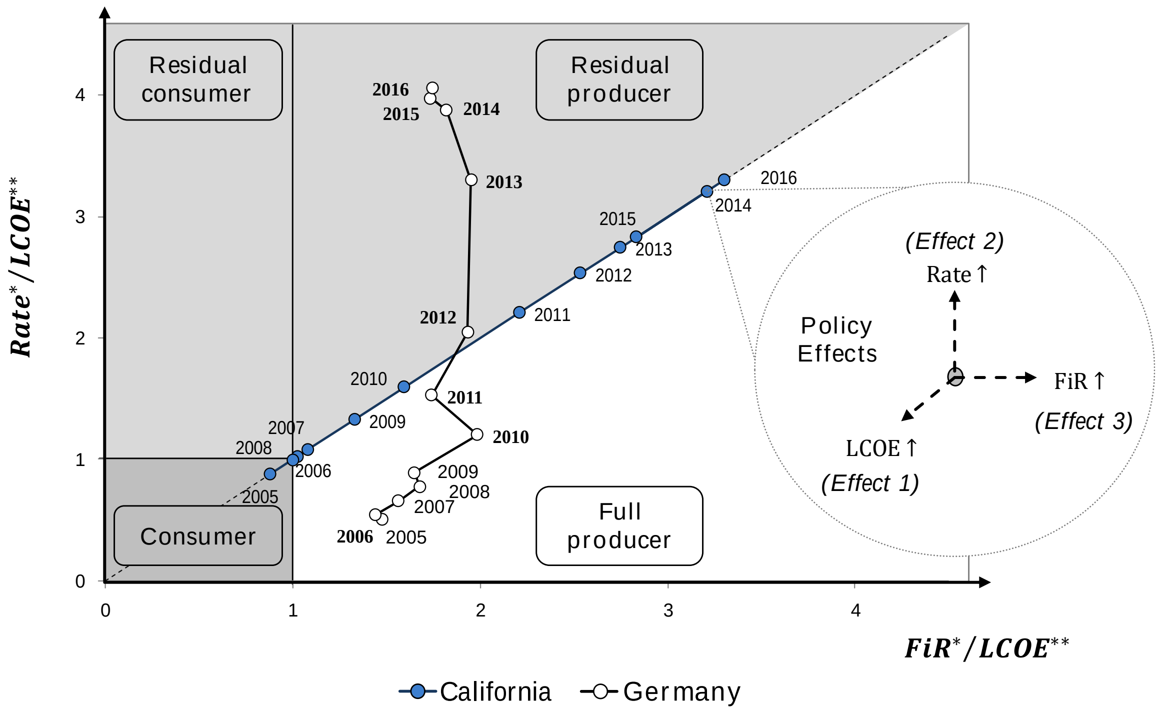

Figure 5: **Framework 'The drivers of residential PV paradigms'**
Illustration depicts Trajectories for California and Germany from 2005 to 2016
(*levelized over investment time horizon; **net levelized costs)

5.2 Paper II: Hybrid Ambidexterity: How the Environment shapes Incumbents' Use of Structural and Contextual Approaches

The policy-induced diffusion of DER technologies such as residential solar PV, and the changing role of end consumers confronts incumbent electricity providers with a business environment that fundamentally differs from what they have been exposed to for almost one century. This development entails the threat of rendering many of the organizational capabilities obsolete that were built up in the past and are exploited to generate value at present. Therefore, utility companies have started to explore ways out of this situation. However, as extensively discussed in the literature, the simultaneous exploration of novel opportunities and exploitation of existing ones creates organizational tensions that need to be addressed by corporate management. While organization science points out that two archetypical approaches, namely structural and contextual ambidexterity, can be used to address these challenges, so far we lack insights into the environmental characteristics that induce firms to focus on either approach, and into whether and how they can be combined.

Based on a comparative, longitudinal case study of the four largest electric utility companies in Germany – RWE, E.ON, EnBW, and Vattenfall (the "Big Four") – the paper shows that firms predominantly focus on structural ambidexterity when they perceive emerging opportunities as requiring organizational capabilities and a culture fundamentally different from their own (cf. Figure 6: lower right corner). In particular, spurred by the nuclear phase-out decision in 1998 and the introduction of the Renewable Energy Source Act in 2000, renewable energy capacity experienced a considerable uptake in the German electricity generation mix. However, these developments were "not taken seriously" (E3[22]) by the incumbent utilities until 2007. With a total share of less than 8% of the growing renewables market, the Big Four adapted their strategy towards "going green" by launching dedicated business units focused on building up a pipeline of renewable projects. These units were deliberately separated from the rest of the organization, often staffed with external hires, and equipped with a budget determined by the top management team. The findings suggests that this approach was chosen for three main reasons. *First*, the firms' culture was coined by a lack of support for renewables in all parts of the organization making it "difficult from the perspective of the companies' DNA to bring together engineers responsible for conventional plants with the entrepreneurs working on renewables" (U30). Hence, separation was deemed necessary to overcome the "strong resistance" (U22) that would have directly killed the initiatives. *Second*, since the organizations had very limited capabilities and experience in renewables, but wanted to ramp up this business fast[23], it was important to specialize and accordingly design the new units "without all the legacy, the personnel processes, and the bureaucracy" (U28) of the main organization. Thereby, separation allowed the firms to accelerate the development of new processes to engineer, build, run,

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[22] The codes E1-E16 and U1-U30 refer to the interviews that were conducted with industry experts and utility representatives. Details can be found in the corresponding section of Annex I.

[23] Between 2008 and 2013, RWE and E.ON alone invested more than US$15 billion in RES projects.

and maintain renewable plants. *Third*, separating the renewables units was facilitated by the fact that the spectrum of available technologies was limited, and the focal technologies had relatively mature characteristics, which allowed corporate managers to quickly decide which renewables to target. As a result, engaging into offshore wind power developed into an industry consensus due to the strong resemblance with the firms' established core business, namely to 'build-own-operate' "large-scale, central plants" (U19).

Despite the gradual increase of their renewable capacity, around 2011 the Big Four faced a situation of "completely eroded" (U12) profit margins in the conventional business due to excessive supply on the electricity market, which led to the necessity to "write down many of the assets" (U29). Moreover, increasingly mature DER technologies, changing consumer preferences, and ongoing policy support jointly spurred the new downstream business. By 2012, 1.3 million residential and commercial customers in Germany had installed solar PV systems, which started to have a noticeable effect on the competitive retail market since it allowed them to displace a significant share of their electricity consumption. Increasingly worried about such load and grid defection[24] scenarios and the growing competition from new entrants as well as established players in other sectors[25], the Big Four faced an environment characterized by a confluence of numerous and uncertain opportunities, and a high distance from the existing organizational culture and capabilities. In sum, the interviews portrayed new downstream as "an incredibly broad field" (U12). In response, the firms launched a series of different organizational initiatives, some of based on structural approaches, others resembling contextual ambidexterity. The empirical evidence reveals that this can be explained by the firms' attempt to leverage the complementarities between structural and contextual approaches, either as part of distinct initiatives in a parallel but isolated, or by merging the ideas of both approaches within a given organizational initiative. These two types are labelled 'split' and 'joint' hybrid ambidexterity (cf. Figure 6: upper right corner).

In particular, while the Big Four all launched new organizational units dedicated to the new downstream business (structural ambidexterity), they also initiated firm-wide efforts to overcome organizational rigidities by promoting cultural change. The latter initiatives followed a contextual approach, providing frontline employees with the freedom to switch between exploration and exploitation activities while leaving the organizational design intact. The goal was to motivate the employees to reflect on their established routines, while fostering the "willingness to quickly respond to ideas and external changes" (U12). Besides pursuing these split hybrid approaches, firms also combined structural and contextual approaches in individual initiatives. For example, they launched initiatives that were separated from the existing business and promoted a distinct culture, but, on the other hand, flexibly drew in frontline employees from different parts of the old business units. These approaches were in line with an open search strategy that included leveraging the distributed

[24] A scenario in which customers "completely get rid of their grid connection eventually" (E10).
[25] E.g. automobile, telecommunication, and software.

attention and expertise of frontline employees by providing them with protected spaces to "work on new projects outside the box" (U26). Whereas a purely contextual approach reduces the role of management to providing an appropriate context that stimulates the employees to find an effective balance between exploration and exploitation, the joint hybrid ambidexterity initiatives observed in this study built on a more active role of senior managers. In particular, interviewees argued that despite a lack of centralized, hierarchical coordination, a certain degree of "top-down support is important" (U26), both in terms of ensuring sufficient supply of resources but also in supporting the initiatives to "quickly bring products to the market as pilots and test them" (U15).

The key outputs of the article are summarized in Figure 6, which maps the two central features of change in the business environment of incumbent firms – namely the number and uncertainty of opportunities, and their distance from the organizational culture and capabilities – to the three archetypical ambidexterity approaches that corporate managers have at their disposal.

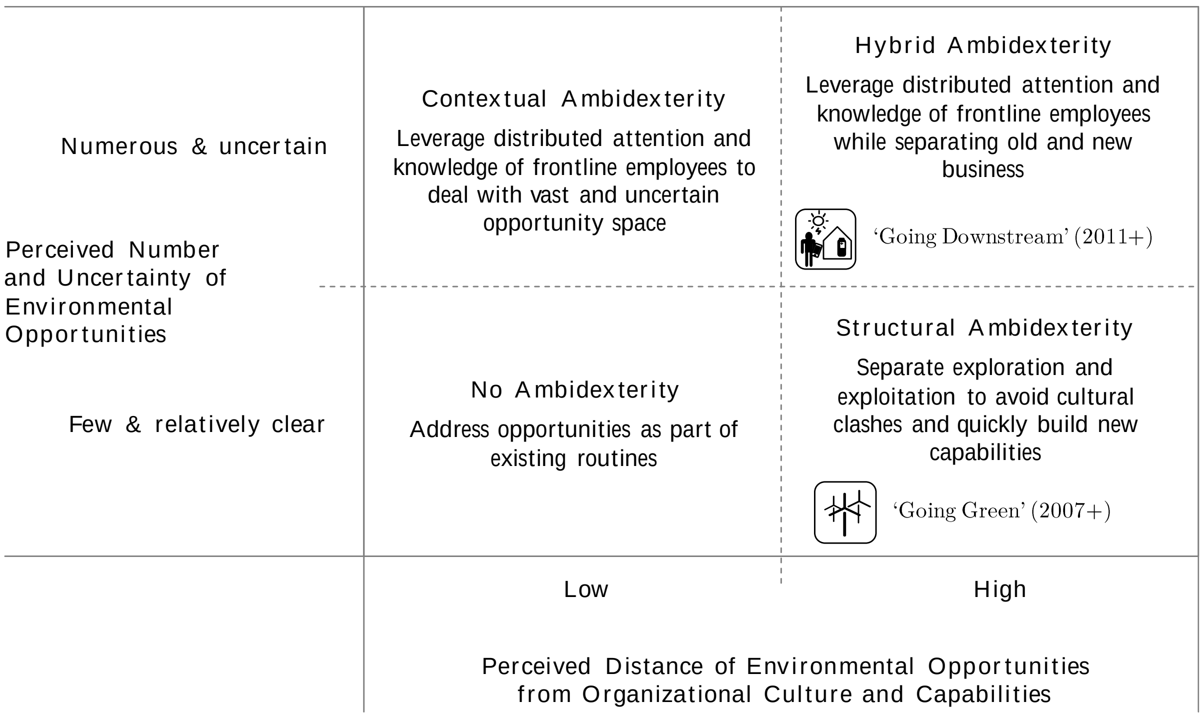

Figure 6: **Framework 'Environmental Antecedents of Organizational Ambidexterity'**

5.3 Paper III: Delineating Policy Mixes – Contrasting the Top Down and Bottom Up Approach along the Case of Energy Storage in California

Given the systemic and complex nature of sustainability transitions such as the decarbonization of the energy sector, their governance usually rests on several different policy instruments that are more or less well coordinated as part of a policy mix. However, despite the growing interest in the assessment and further development of policy mixes, so far there has been no clear guideline as to how the key elements of a given mix – namely its strategy and its instruments – can be identified and operationalized. This lack of methodological consistency is problematic, since it may lead to overly complex or oversimplified representations of real-world policy mixes, complicate or prohibit the comparison of findings across studies and question their degree of generalizability. In sum, the lack of clarity about how to delineate the analytical scope of the focal construct may undermine the legitimacy of the emerging research stream elaborating on policy mixes for sustainability transitions. To address these challenges, this paper explores and synthesizes different boundary setting approaches found in the literature, thereby providing a common ground for future policy mix analyses. Since a significant share of empirical studies is coined by a lack of analytical clarity and an implicit use of the key constructs, the paper starts from a simple assumption: policy mixes are probably best known to those who shape its elements, namely policy makers, and those who are affected by it, namely the actors shaping the underlying innovation system. Building on this notion, Figure 7 introduces a conceptual framework that contrasts the two archetypical approaches to study policy mixes, namely the 'top down' and the 'bottom up' approach.

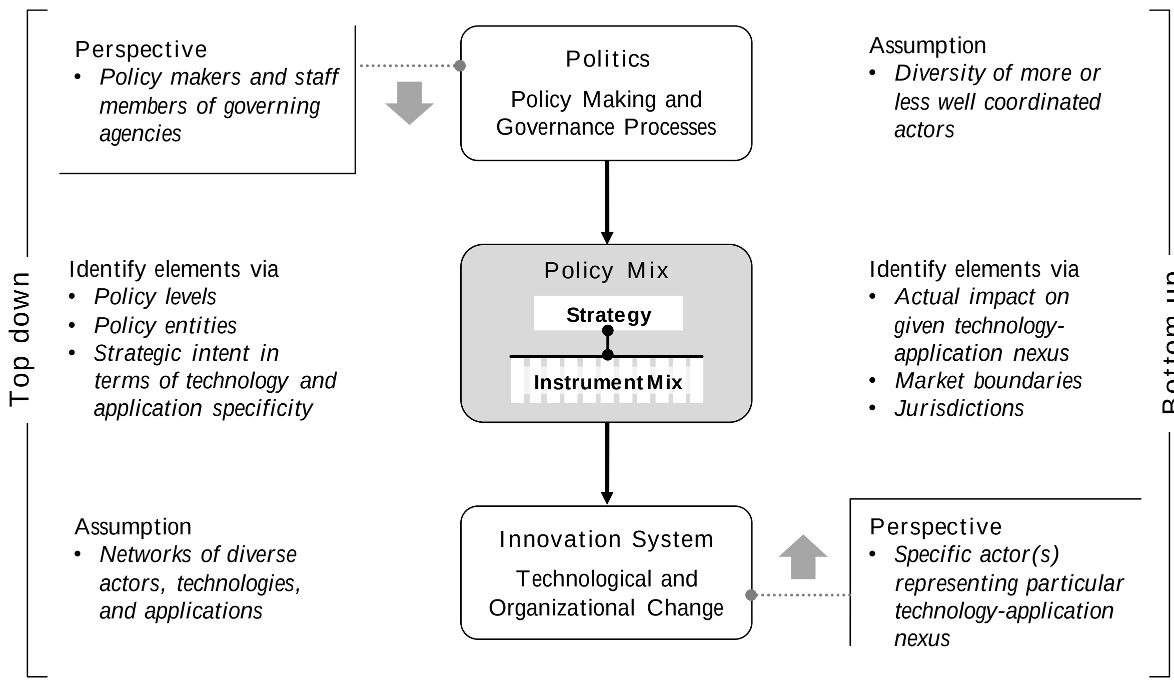

Figure 7: **Framework 'Deriving Policy Mixes Top Down vs Bottom Up'**

To explore which differences the two approaches entail in terms of the analytical process and its outcome, the paper elaborates on the elements that constitute California's policy mix for energy storage. This case is selected since it includes the key building blocks of a policy mix, namely several policy instruments embraced by an overarching strategy, is characterized by non-trivial interactions between its elements due to the confluence of multiple goals, governing entities and governing levels. In addition, the fact that the energy storage domain is composed of several sub-technologies (e.g. batteries, flywheels, pumped hydro) and is associated to several applications (e.g. increase of self-consumption, peak shaving, seasonal storage) which can be assessed by different micro- and macro-level metrics (e.g. economics, T&D deferral, renewable integration) renders it a valuable case to assess differences in delineating the relevant elements of a policy mix. The reason is outlined in Figure 8. The top down approach adopts the perspective of the policy maker who is usually interested in successfully governing the larger innovation system, in this study, the case the domain of energy storage in California. By contrast, the bottom up approach starts from the view of an individual firm or consumer, who usually occupy a certain technology-application nexus and are characterized by individual preferences and goals. For this paper, the selected nexus was represented by residential homeowners who assess the economics of different solar+storage technology bundles.

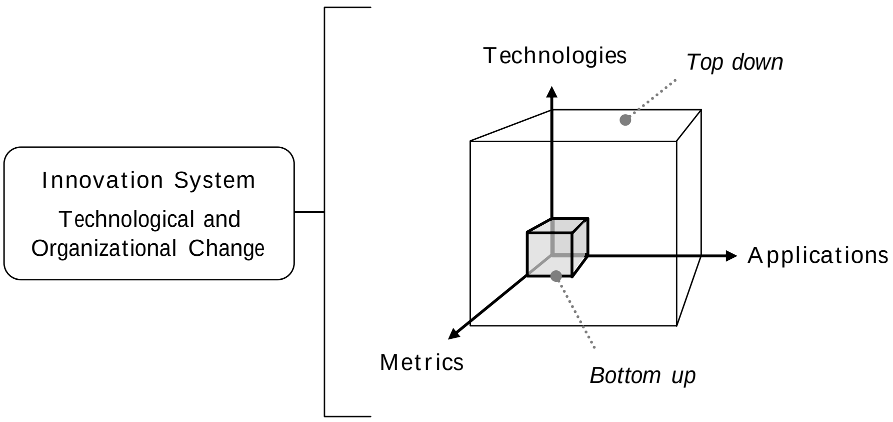

Figure 8: Scope of the Innovation System following Top Down vs Bottom Up Approach

Based on a longitudinal case study and a techno-economic model, the article yields three particular findings. *First*, the two top down and the bottom up approach may lead to fundamental differences in the identified policy mixes. In particular, while the top down (14 strategies and 27 instruments) and the bottom up approach (14 strategies and 11 instruments) revealed a similar number of policy elements, the overlap was fairly small (three strategies and one policy instrument).

Second, while this result may partly be explained by the specific case selection as outlined above, it serves well in highlighting the individual strengths and weaknesses of each approach. In particular, the analysis suggests that the top down approach may be of great use to shed light on horizontal and vertical coordination challenges within a given policy mix, as it allows researchers to trace the evolution of a particular policy mix as well as the governing rational behind it. However, analysts should be careful of not implicitly assuming a 'green field' for policy makers, as especially emerging innovation systems are initially governed by the existing 'regulatory maze' (Carl et al., 2012) rather than a well-designed, and hence easily delineable policy mix. By contrast, the bottom up appears to well suited to uncover the joint effect of instruments independent from which policy field or entity they are governed. Therefore, by adopting the perspective of the actors in the innovation system, analysts can detect both the positive (reinforcing) as well as the negative (undermining) interactions between individual policy instruments. This strength has been shown for the case of the policy mix shaping residential solar+storage in California. Specifically, even though the Net Metering (NEM) program was not intended to affect the energy storage domain – and hence would not be considered part of the top down energy storage policy mix – this policy instruments strongly affects the economics of distributed energy storage systems. In particular, by offering the electricity grid as a free of charge alternative, it undermines the competitiveness of residential energy storage coupled with PV systems and hence the effectiveness of support instruments that target this part of the innovation system. Furthermore, the bottom up approach is particularly valuable when analyzing how policy affects the innovation system in its initial phase, when a dedicated policy mix is not yet in place due to uncertainty about the underlying technologies, niche markets, and new entrants. However, despite these advantages of adopting an actor perspective with a relatively clear position in the innovation system, the informative value of a policy mix derived by the bottom up approach is inherently restricted to the selected technology-application nexus, and may be additionally narrowed down by the choice of the metric to operationalize the policy impact. Hence, when assessing policy mixes based on the bottom up approach, analysts should be aware that they adopt an idiosyncratic approach on the policy mix. This is particularly relevant for determining policy mix characteristics such as consistency or comprehensiveness.

Third, due to their complementary characteristics, it may be worthwhile to combine the top down and the bottom up approach. As demonstrated in the paper, this 'hybrid approach' is already used in California, where the leading governing agencies have launched programs to leverage the expertise of a diverse set of stakeholders and integrate their suggestions and concerns into the policy making process. The 'Energy Storage and Distributed Energy Resources' (ESDER) initiative is an example of this approach, that integrates the top down view of legislators (shaping strategic objectives) and regulators (implementing and administrating the policy instruments), with the perspective of actors in the emerging energy storage domain. Another example can be found in a recent paper, which elaborates on the offshore wind policy mix in Germany by combining a top down approach with multiple bottom up perspectives captured in a range of stakeholder interviews (Reichardt et al., 2016).

5.4 Paper IV: How Policy shapes the Diffusion of Residential PV + Battery Systems – An Agent-based Simulation of California's Energy Transition

This paper builds on the analysis conducted in Paper I, but takes a forward-looking approach and significantly expands the scope of policies and technologies based on the insights of Papers II and III. In particular, the article elaborates on how alternative policy mixes (bundles of strategic policy goals and policy instruments) affect the diffusion of residential solar PV and battery storage systems in California. Moreover, the paper looks at how effectively these mixes address two overarching policy goals, namely i) providing a reliable grid infrastructure, and ii) maintaining socio-economic fairness. To adequately depict the adoption decisions of residential households, the paper develops a sophisticated agent-based model (ABM) in order to take behavioral aspects of the socio-technical system and system-level feedbacks into account. In particular, the model includes residential households (~12 million rescaled by a factor of 10,000), the wholesale and retail electricity markets, the three largest investor owned electric utility companies (comprising >80% of the market), and the regulatory agency CPUC in the simulation. The ABM is calibrated with historic PV adoption and electricity market data from California between 2005 and 2015.

Based on a detailed sensitivity analysis of the major policy instruments (PI), the paper studies the impact of three particular policy mixes (PM) for the period between 2016 and 2030. The first policy mix "Policy Freeze" (PM1) assumes the policy parameters of 2016 remain unchanged until 2030 and is subsequently used as a reference case for illustrative purposes. The second policy mix "Current Path" (PM2) assumes that all changes to the current policy mix in California will be implemented as announced. These include a phase-out of the upfront support for solar PV and battery systems, a switch from tiered rates to time-of-use rates, and a phase-out of the Net Metering scheme (for details cf. Paper I). Beyond that, no further adaptations to the policy mix are implemented. The third policy mix "Smart Path" (PM3) is deliberately designed to find a balance between the overarching policy targets. In particular, it follows from an in-depth sensitivity analysis of all major policy instruments and combinations thereof, namely upfront grants (PI1), electricity rate design (PI2), and feed-in remuneration design (PI3). Rather than following an optimization approach, PM3 intends to serve illustrative purposes, which is why the number of changes in policy instruments compared to the reference case PM1 was limited. In essence, PM3 only differs from PM1 in terms of introducing a fixed charge of 20$/month for all residential PV owners, and replacing Net Metering by a Feed-in Tariff that is gradually phased out from the retail to wholesale rate over ten years. The preliminary simulation results of PM1-PM3 are illustrated in Figure 9.

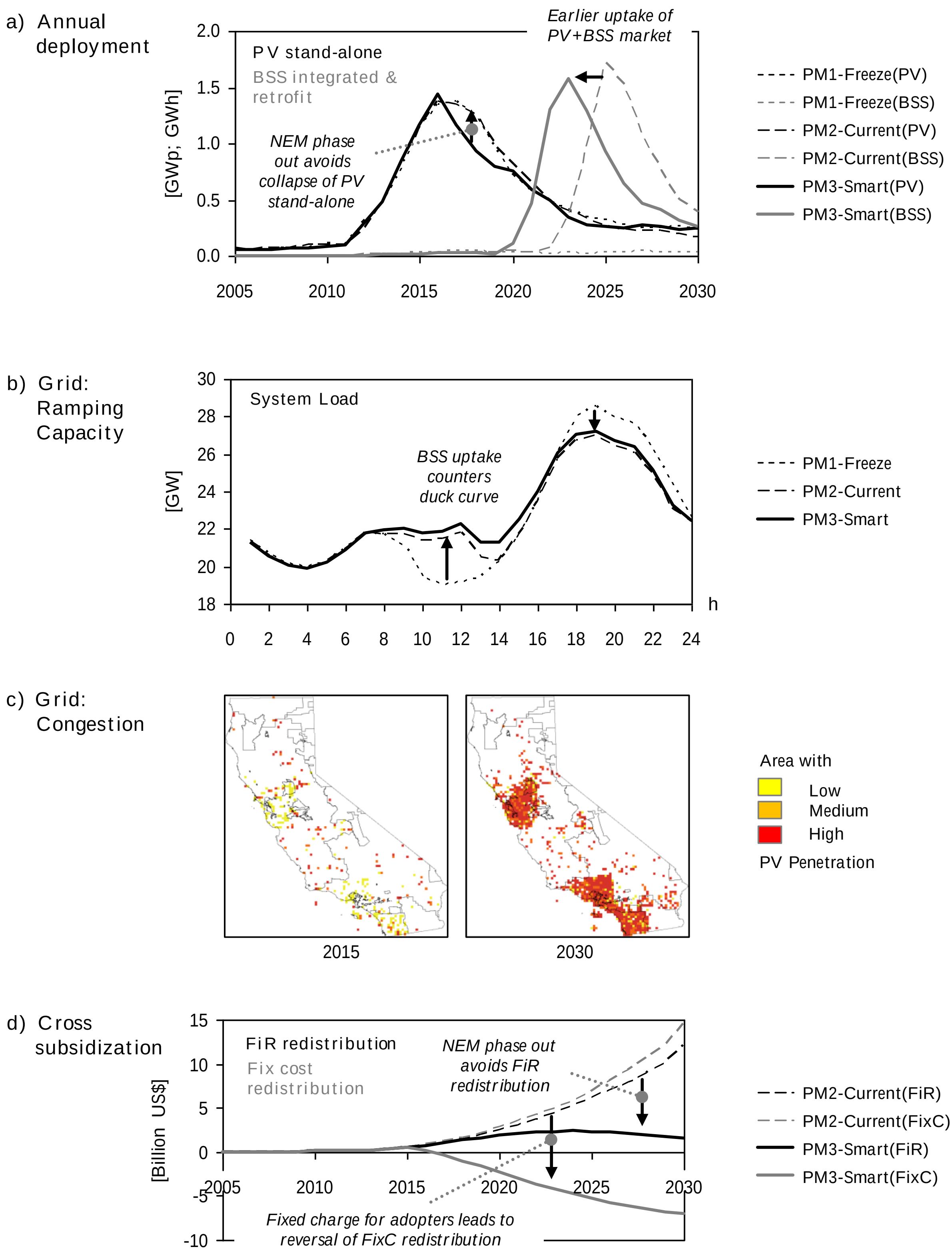

Figure 9: Results of Agent-based Model for three Policy Mixes PM1, PM2, PM3
(if PM1 not shown, assume identical values as for PM2)

The results illustrate that seemingly minor differences in the composition of policy mixes significantly affect the diffusion of residential solar PV and battery storage systems in California, which may entail profound effects for the state's electricity infrastructure. In addition, the preliminary findings concerning the "Smart Path" compared to both the "Current Path" and the "Policy Freeze" case suggest that carefully designed policy mixes have the potential to spur the diffusion of clean technologies while simultaneously mitigating some of their lagged and potentially adverse effects on the system-level. In particular, PM3 spurs a timelier uptake of integrated solar PV and battery systems due to the phase out of the predominant feed-in remuneration (FiR) scheme. Using a gradual rather than an instantaneous phase out of the FiR instrument, a collapse of the stand-alone PV market can be avoided and subsequently replaced by the demand for integrated systems. Finally, PM3 significantly reduces or even reverses the cross-subsidization between solar PV adopters and non-adopters due to the introduction of a monthly standby charge. This paper provides a first attempt to illustrate how computational tools can be used to support policy makers in the design of policy mixes for complex socio-technical systems. The agent-based model can be applied in a variety of contexts and may allow decision makers and analysts to explore the antecedents and implications of the growing residential PV+battery market.

6 Conclusion

The objective of this dissertation is to assess *how policy mixes affect technological change and organizational learning* in the energy sector. This chapter carves out the key contributions that arise for theory – in particular for the literature on policy mixes and organizational ambidexterity – and for practice – in particular for policy makers, corporate managers, and end consumers.

6.1 Contributions to the Literature

Policy Mixes for Sustainability Transitions

This dissertation adds to the literature on policy mixes for sustainability transitions (Rogge and Reichardt, 2016), which looks at the elements, processes, and characteristics associated to the coordination of multiple policy instruments towards a set of common objectives. In particular, Papers I, III, and IV advance the literature both methodologically and conceptually. The three most relevant aspects are discussed in the following.

First, this work proposes a systematic analytical framework and process to delineate the elements of policy mixes. In particular, Paper III introduces the notion that policy mixes can be assessed from two different angles, namely from the view of policy makers and the perspective of the actors who shape innovation in the underlying innovation system[26]. Elaborating on this "top down" / "bottom up" dichotomy, the paper emphasizes that the two approaches can be used to highlight different aspects of the policy mix phenomenon. While the top down approach seems better suited to derive the elements of a policy mix that are geared towards a particular innovation system, it may fall short of capturing the interactions across policy mixes that pursue different strategic objectives. The opposite appears to be true for the bottom up approach, which focuses on a specific technology-application nexus within an innovation system and thus captures both the intended and the unintended interactions between policy elements regardless of which policy mixes they are part of. The empirical data reveals that scholars may leverage these complementarities by combining the top down lens, with the bottom up views of industry stakeholders, which depends on the specific research design. Based on the clear guidelines for how the two approaches can be applied in practice, this work may significantly increase the methodological consistency of studies in the policy mix literature.

Second, this dissertation provides a more nuanced perspective on the actors and entities who shape or are affected by policy mixes. As indicated by the stylized top down / bottom up dichotomy, this work suggests that actors should be incorporated more explicitly in the policy mix framework rather than treating them as a mere dimension such as time or geography (cf. (Rogge and Reichardt, 2016,

[26] Recall the distinction between "sustainability transitions" and the "energy technology innovation system" (ETIS) in Chapter 2.

pp. 1629–1630)). In particular, policy makers and the organizational structure of the key governing agencies could be framed as a "missing link" between policy processes and elements (strategies, instruments). In addition, explicitly incorporating the stakeholders who drive innovation in the focal innovation system can be regarded as a prerequisite of understanding the co-evolution between policy mixes and sustainability transitions.

Third, in addition to the contributions to qualitative research on policy mixes outlined above, this dissertation also holds a number of important insights for more quantitative approaches. As shown in Papers I and III, techno-economic modelling can be used to study the combined effect of multiple policy instruments along different metrics while taking their individual design features into account. This may render the assessment of important policy mix characteristics, such as consistency, more tangible, which may increase the relevance of policy mix research for policy mix design and thus facilitate the dialog with practitioners. Furthermore, as shown in Paper IV, the opportunities provided by agent-based modelling may spur ex ante assessments of policy mixes and thereby support the transition of complex socio-technical systems such as the energy sector. This dissertation provides a systematic approach to model the impact of policy mixes ex ante, while quantifying the trade-offs between different policy goals, and treating central elements of the policy mix as endogenous rather than as exogenously given. In sum, the analysis shows that the individual characteristics of each policy instrument, rather than the instrument type per se, determine how it interacts with the other elements of a larger policy mix. Hence, explicitly taking design features of instruments into account should be adopted as a standard among scholars who study the interactions among elements of policy mixes.

Organizational Ambidexterity

This work contributes to the literature on organizational learning and ambidexterity (O'Reilly and Tushman, 2013), which studies how firms address the challenges that arise from pursuing exploration and exploitation activities at the same time. In essence, Paper II reveals that whether a given organization invests in structural or contextual ambidexterity depends on the nature of the changing business environment the organization is confronted with. The following three aspects further elaborate on this finding.

First, firms seem to draw primarily on structural elements when they conclude that the new opportunities in their environment are manageable in their amount and relatively clear, but distant from the organization in terms of its culture and capabilities. The reason is that structural ambidexterity involves creating distinct business units, which allows firms to maintain different sub-cultures within its boundaries. In addition, the limited number of novel opportunities allows top management to quickly identify strategic priorities and assign them to the corresponding organizational units. By contrast, if the number of opportunities is large and their features unclear or uncertain, firms tend to draw primarily on contextual elements, which allows them to leverage the distributed attention, knowledge and capabilities of frontline employees throughout the organization. In case the environment is characterized by opportunities that are both distant in terms of capabilities and culture *and* large in number and uncertain, firms can combine elements of structural and contextual ambidexterity.

Second, further elaborating on the observation that firms may combine structural and contextual approaches to leverage their respective advantages, this work provides detailed insights into the underlying mechanisms of how firms implement these *hybrid ambidexterity* approaches. The empirical data analyzed in this thesis indicates the existence of different forms of hybrid ambidexterity. On the one hand firms may draw on *split hybrid* approaches, which means that they pursue structural and contextual ambidexterity at the same time but as part of isolated initiatives. For example, they may set up a dedicated business unit to enter a new technological field, while simultaneously spurring cultural change programs that employees pursue part-time. On the other hand, firms may engage in *joint hybrid ambidexterity*, which means that they merge selected elements of structural and contextual approaches. For example, they may implement new forms of collaboration such as loose network structures or permeable venturing units that clearly separate exploration and exploitation activities and hence leverage specialization, but provide employees with the flexibility to join and leave the corresponding initiatives.

Third, the empirical evidence suggests that firm-level factors may mediate the relationship between environmental change and a firm's response in terms of organizational ambidexterity. In particular, Paper II shows that the differences in both the timing and design of ambidexterity approaches may be traced back to the firm's geographic location and scope. As a result, a given environmental discontinuity may affect individual firms to a different extent, even if they are active in the same industry and similar in other aspects. This finding entails important implications for multi-national firms, which are active in several markets. Paying close attention to managers in subsidiaries who demand a higher speed of responding to local environmental challenges may foster geographically diversified firm renewal and protect the organization from losing its competitive advantage in changing markets.

6.2 Implications for Policy Makers, and Policy Analysts

In light of the fundamental transition required in the energy sector, policy makers have a pivotal role in setting the course. As concluded in a previous report on DER, "[c]reating a level playing field for centralized and distributed resources will require significant changes in electric utility business models and electricity markets, as well as other changes in regulation and policy to adapt to rapidly evolving technology" (Newcomb et al., 2013, p. 41). To live up to this expectation, this dissertation holds 5 practical implications for policy makers, regulators, and the analysts supporting them.

First, policy makers should thus develop a vision for DER which could subsequently be translated into a dedicated strategy and corresponding mix of policy instruments for this domain. The reason is that in recent years a substantial share of the electricity infrastructure has started to move "behind-the-meter" (BTM). This includes a shift out of the realm of incumbent players in the power system such as regulators and utilities. Market forecasts indicate that this development will continue at an accelerated pace[27], which entails the risk of lock-ins into technological configurations that turn out as sub-optimal in the long run. Given the considerable lifetime of energy system components[28], the DER vision could inform a "prosumer strategy" as suggested in the study of residential solar PV in Paper I. This is not a trivial task and should thus include a public debate, since it entails multiple trade-offs of societal importance. For example, while larger residential solar PV systems leverage economies of scale, decrease acreage sealing, and increase the decarbonization pace, they may also entail stronger cross-subsidization effects and higher costs for infrastructure transformation. Notwithstanding the challenge of achieving a consensus, the DER vision would provide policy makers with a guideline on how to adjust policy mixes, which includes removing skewed incentives and sending appropriate price signals to leverage the full range of services DER can provide. This could facilitate turning the infrastructure into a "plug-and-play" system that allows technologies to diffuse more rapidly and ultimately overcome the traditional divide between BTM and FOM.

Second, to do so, policy makers should recognize the specificities of DER (cf. Chapter 3) and foster the corresponding innovation systems[29] accordingly. A particularly important aspect to be considered is that the development of DER technologies in terms of cost and performance may be driven more by innovation spillovers and diffusion in other sectors and markets, than by the demand for DER in the energy sector. For example, much like the dominant design and costs of conventional backup electricity generators in residential households are predominantly driven by developments of the internal combustion engine in the automobile industry, the same seems to hold true for the development of stationary battery storage systems, which are basically adaptations of products used in consumer electronics and electric vehicles. In addition, it has been shown that the successful development of energy technologies with complex product architectures (such as DER) strongly depend on learning-by-using, i.e. incremental innovations that arise from interactions at the user-producer interface (Huenteler et al., 2016). This learning mode is particularly difficult to realize in the energy sector, a socio-technical system that has been engineered to minimize errors and is characterized by prohibiting trial-and-error learning in case the larger system is affected. This is why policy makers such as in California (cf. Paper III) set procurement targets for battery systems and have created niche markets for novel entrants such as DER aggregators, which integrate distributed energy generation and storage technologies into virtual power plants and bid into wholesale and ancillary services markets.

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[27] In a recent report Bloomberg New Energy Finance forecasts the following: "By 2024, two thirds of all installed energy storage capacity is behind-the-meter"; "PV+storage is a significantly larger market opportunity than using energy storage for commercial and industrial (C&I) demand charge reduction"; annual deployment of BTM PV+storage at 7GW/16GWh, corresponding to 70% of the US$8.3 billion storage market in 2024 (Bloomberg, 2016).

[28] For example, once installed a solar rooftop system often remains untouched for 25 years – if abstracting from potential replacements of parts of the balance-of-system (BOS).

[29] One example is the "Energy Technology Innovation System" introduced in Chapter 2.2.

Third, when designing such policy mixes, policy makers should take three important aspects into consideration, namely comprehensibility, credibility, transparent communication. As suggested in Paper III, this can be achieved by complementing the introduction of new policy mixes with an equivalent reduction in existing "regime" policy instruments, and by simplifying legislation and regulation so that it can be understood by new entrants such as DER vendors. In addition, these factors may enable end consumers to identify, understand, and trust the policy support that is available, and independently assess the economics of alternative DER investments. In turn, they can actively approach, compare, and select the most attractive DER vendor. This could help reduce customer acquisition costs while creating societal "buy-in" to the energy transition by providing end consumers with opportunities to participate, which could ultimately increase the resilience of policy mixes across administrations.

Fourth, this dissertation reveals the importance of integrating industry stakeholders and end consumers into the policy making process around DER. The reason is that actors in the innovation system are usually best equipped to estimate the potential effect of policy instruments and their particular design, since they are closest to the technologies, their potential applications, and the associated business models. As shown in Paper III, the agencies responsible for governing California's electricity sector have started to make active use of systematic, long-term stakeholder engagement processes in order to collect feedback for how to reshape the state's energy storage policy mix and increase the pace of implementing the necessary institutional changes. In addition, California also provides a good case to study horizontal coordination between agencies and that inter-agency task forces may render centralization and the formation of dedicated entities unnecessary. Studying the lessons learned from these initiatives, such as how to ensure a balanced participation of incumbent and new firms as well as the civil society, could be of great value for policy makers in other jurisdictions.

Fifth, to successfully govern the emerging DER domain, policy makers should understand how their decisions impact firms and end consumers, whose interplay determines pace and direction of technology development and diffusion. Given the interaction between various policy interventions, analysts seeking to support policy makers should adopt an integrated lens and study policy mixes rather than analyzing individual instruments and deriving recommendations that would work only in isolation. This dissertation makes a case for the use of computation-based analyses to inform policy makers about the impact of alternative policy mix designs. In particular, Papers I, III and IV have shown that techno-economic and agent-based models can be used to quantify inconsistencies between policy instruments, develop foresight capabilities to anticipate the diffusion of novel technologies, and estimate the need and timing of infrastructure adaptation. However, using these tools does not imply an overly simplistic or mechanistic understanding of the processes that shape real-world policy mixes (Flanagan and Uyarra, 2016). In other words, attempting to quantify the impact of policy mixes does not render iterative policy making or 'muddling through' obsolete (Lindblom, 1979, 1959). Instead, it may be regarded as a complement to traditional political and societal sensemaking processes, and thereby help policy makers 'muddle through' faster, more transparent and in a more systematic way.

6.3 Implications for Corporate Managers and Executive Education

Sustainability transitions, which may be more or less affected by public policy mixes, will continue to fundamentally transform the business environments of firms across sectors. At least three lessons for corporate managers arise from the analyses conducted in this thesis.

First, as described in Chapter 3, the emergence of DER opens up a range of new business opportunities for firms that are prepared to take advantage of the "new downstream" business. While incumbent firms in the energy sector such as electric utilities or technology providers have a competitive advantage in terms of an existing customer base and a thorough understanding of the "regulatory maze" (Paper III), they often fail to leverage these resources for a head-start in the DER domain. As shown in Paper II, the reason is often not a lack of recognition of the changing business environment per se – as often claimed in the public debate following the argument that utilities have "overslept" the energy transition – but rather a misinterpretation of what these changes imply in terms of strategic renewal and organizational adaptation. Hence, managers in electric utilities around the world could apply an important lesson from their colleagues in DER lead markets such as California, Germany, or Australia, namely that they "[…] could greatly benefit if they did not treat PV as just another source of electricity generation in competition with traditional sources (as they do today), but as a strategic gateway into the emerging distributed generation and service market" (Richter, 2013, p. 456).

Second, it seems that corporate managers in incumbent firms beyond the energy sector could benefit from studying how Germany's Big Four electric utilities have responded to the challenges imposed by the uptake of renewable energy and the emergence of the new downstream business. For example, there are striking similarities between the organizational response of incumbent automobile manufacturers in terms of electric mobility, and the initiatives launched by firms in the German utility industry around 2007 in reaction to the uptake of renewable energy technologies. For example, some firms (such as BMW) have clearly made use of structural ambidexterity by setting up dedicated business units and promoting them under separate brands for electric vehicles (the i series) to overcome the organizational rigidities arising from a long tradition of building internal combustion engines. However, similar to the situation of the electric utilities ten years ago, the continuing success of the current business model in the automobile sector – which rests on exploiting capabilities and resources that have been built up over the last century – entails a double threat. On the one hand, investments into the new business units are unlikely to reach a level that allows them to compete with and ultimately replace the current core business. On the other hand, based on the trend towards the electric drive train but going beyond the technological phenomenon as such, numerous emerging opportunities could spur alternative forms of mobility. Examples include different car sharing models, mobility flat rates combining public and private transport, and autonomous driving. While incumbents (such as Daimler) have started to explore the large but uncertain opportunity space (cf. CASE strategy) in way similar to and partly overlapping with electric utilities in response to the new downstream business (cf. car2go vs Croove), it remains to be seen whether these organizational initiatives will be successful in gradually transforming the entire organization in light of the fundamentally changing business environment or whether they will remain niche initiatives that are eventually "killed by the firms' antibodies" (cf. Paper II, U19).

Third, corporate managers should employ the concept of hybrid ambidexterity derived in Paper II of this thesis to make sense of their changing business environment. In particular, it provides senior management with a structure and a toolset for how to devise appropriate organizational ambidexterity approaches tailored to the firm's characteristics. In addition, the concept could be further developed into a practitioner-oriented, stylized decision making framework that may be introduced as a potential complement to established business school frameworks such as disruptive innovation (Charitou and Markides, 2003). Moreover, the further exploration of the presumable variety of joint hybrid ambidexterity approaches could yield a number of interesting teaching cases to be used in executive education programs.

6.4 Implications for End Consumers

Given their central role in the emerging DER domain, this dissertation holds a number of implications for end consumers who could turn the formerly passive demand side into an active part of the energy transition.

First, consumers should apply a healthy degree of skepticism concerning the value proposition of DER, carefully weigh different offers against each other, and in case of doubt, consider investing once DER have become more mature. For example, in many countries the market for rooftop solar systems is very mature, and residential homeowners can decide whether to buy the system themselves, make use of a bank loan, enter a purchase power agreement (PPA), lease the system from a third-party owner, or participate in a community solar PV project. Given that the overall DER market is still in an 'embryonic' stage, consumers should keep in mind that e.g. a lack of standardization may inhibit compatibility between components of different DER vendors, and prohibit full modularity and gradual upgrades of existing BTM energy systems. Moreover, especially when considering larger DER investments (such as retrofitting a solar PV and heating system) consumers should consult with an independent expert or seek advice from consumer protection agencies to understand the most important technical characteristics. In addition to seeking advice, customers should also inform about the opportunity to benefit from public support schemes. The latter are available in many countries, especially when it comes to energy efficiency upgrades and demand side management.

Second, as elaborated in Papers I and IV, when considering the installation of a solar PV system consumers should think about whether the electricity may meet additional demand beyond its current end use in the household or commercial facility. The reason is that it may make economic sense to opt for a larger PV system (or an installation that faciliates upgrading) that is able to supply electricity for energy services that have so far been covered by conventional energy sources, such as replacing the oil boiler with an efficient heat pump. The same holds true in case the electricity consumption patterns are likely to change in the near future, for example due to the purchase of an electric vehicle or the participation in FOM services.

6.5 Limitations and Further Research

The following section discusses the key limitations[30] of this thesis, most of which relate to the fact this dissertation predominantly builds on case study research. On this basis, several promising avenues for future work are outlined.

First, the insights derived in this thesis are based on a specific case, namely DER. As introduced in Chapter 3, this case is characterized by a number of distinct features that may question to which degree the findings can be transferred to other technologies, technology domains or sectors. For example, it may be that an identification of the elements of policy mixes may be less challenging when the underlying socio-technical system is less complex than in the electricity sector. Other than that, it may be that the impact of environmental change on organizational adaptation may be less deterministic in industries that are less regulated and hence less driven by the impact of policy than in the energy sector. Future research could therefore analyze sustainability transitions in other sectors such as food, manufacturing, or transport, and study the changing interplay between policy makers, firms, and end consumers therein.

Second, in this thesis, the scope of DER was narrowed down to residential solar+storage systems. As indicated in Chapters 2.2 and Chapter 3, due to its large number of underlying technologies and associated applications, the emerging domain of DER holds the potential to reveal a range of further insights, such as the emergence of complementarities between individual technologies. These analyses promise valuable implications for how policy makers and industry could spur the diffusion of clean technologies and overcome carbon lock-in.

Third, since the findings presented in this thesis rest on empirical data from California and Germany it is unclear to which degree they may apply in other contexts, especially countries that in the 'non-Annex I' category of the UNFCCC. As highlighted in Chapter 3.4, both California and Germany represent high-income countries, which renders them more likely to become niche markets for and suppliers of DER technologies. Hence, an interesting avenue for further research could be to assess under which circumstance a DER domain emerges in the developing world, and which implications it entails for policy mixes and firm strategies in these states. Prior research has indicated that DER may provide the basis of rural micro grids in previously non-electrified regions, and allow states to leapfrog constructing a centralized grid infrastructure while tailoring the formal and informal institutions to a decentralized system. In addition, assuming a simultaneous uptake of DER in different countries, it could be interesting to scrutinize potential spillover effects between regions.

[30] More paper-specific limitations and opportunities for further research are provided in Annex I.

7 Overview of Papers

The four articles included in Annex I are shown in Table 4, including the target journal and their current status in the publication process as of February 28, 2017.

Table 4: Overview of the papers included in the dissertation

#	Title	Authors	Journal	Status
I	How feed-in remuneration design shapes residential PV prosumer paradigms	Ossenbrink, J.	*Energy Policy*	Published, cf. Vol. 108, 2017 pp. 239-255
II	Hybrid Ambidexterity: How the Environment Shapes Incumbents' Use of Structural and Contextual Approaches	Ossenbrink, J. Hoppmann, J. Hoffmann, V. H.	*Organization Science*	Under Review since 11/2016 Revise and Resubmit until August 1, 2017
III	Delineating policy mixes – contrasting the top down and bottom up approach along the case of energy storage in California	Ossenbrink, J. Finnsson, S. Bening, C.R. Hoffmann, V.H.	*Research Policy*	Invited to Special Issue Under Review since 04/2017
IV	How policy shapes the diffusion of residential solar+storage – An agent-based simulation of California's energy transition	Ossenbrink, J. Schwarz, M. Knoeri, C. Hoffmann, V.H.	Targeted towards *Nature Energy*	Conference Paper presented at Eu-SPRI 2017 and IST 2017

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Annex I: Papers

Paper I

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How Feed-in Remuneration Design shapes Residential PV Prosumer Paradigms

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Abstract

As part of their clean technology and decarbonization strategies, numerous countries have introduced feed-in remuneration (FiR) schemes to spur the deployment of solar photovoltaics (PV). However, in light of rising retail electricity prices and falling costs for rooftop solar installations in recent years, policy makers and regulators face the difficult task of deciding when and how these schemes should be amended or phased out. To understand how such actions might shape the role of residential solar in a changing electricity system and the resulting economics, we study how the design of FiR schemes affects optimal PV system sizes. To illustrate our approach, we draw on empirical data on the FiR policies of Net Metering and Feed-in Tariffs from California and Germany between 2005 and 2016. Using a techno-economic model and a conceptual framework, we show that FiR design and its interplay with retail electricity prices and PV system costs jointly determine whether residential PV installations are economic, how they are sized, and which prosumer paradigms they spur. Our analysis holds numerous implications for policy makers and advisors responsible for redesigning or adapting existing FiR mechanisms, as well as for the stakeholders of an emerging ecosystem based on residential solar PV.

Keywords

Residential solar photovolatics, prosumer, feed-in remuneration, Feed-in Tariff, Net Metering

Highlights

- We study the impact of feed-in remuneration on optimal residential solar PV sizes.
- Feed-in design affects both economics and optimal self-consumption levels.
- A framework illustrates combined effect of feed-in design, retail rates, and LCOE.
- Data from California and Germany reveals that framework is applicable and relevant.
- Policies shape prosumer paradigms and their role in an emerging grid.

1 Introduction

Whether residential solar PV has a material effect on the electricity sector in countries around the world strongly depends on where PV systems are deployed within the grid, and how they operate throughout the day (Bronski et al., 2015). To govern these aspects, which are central for the system integration of residential solar, the design of existing feed-in remuneration (FiR) policies needs to be amended, incentivizing PV owners to align the operation of their behind-the-meter (BTM) installations with the electricity grid infrastructure in front-of-the-meter (FOM) (Couture et al., 2015; Rickerson et al., 2014). Introducing such a policy change, however, is not trivial, since policy makers are currently confronted with a vexing challenge. Despite significant cost decreases in PV technology over the last decade, a simple phase-out of the current "first generation" FiR schemes, such as Net Metering (NEM) and Feed-in Tariffs (FiT), would render residential solar PV uneconomic in many geographies (IRENA, 2015). The reason is that "avoided costs"[1], a commonly suggested alternative feed-in compensation level, are often not sufficient enough to earn back the levelized cost of electricity (LCOE) generated by a typical rooftop PV system. Replacing the current FiR instruments with novel remuneration schemes that, for example, expose PV investors to compensation levels that are time-variant or depend on negotiations about the "fair value of solar" could translate into a temporal bust of the evolving ecosystem around distributed solar (Al-Saleh and Mahroum, 2015; Drabkin et al., 2015; Trabish, 2016).

As a result, policy makers and regulators have begun to amend existing FiR schemes in incremental steps[2] (Kreycik et al., 2011; Rodrigues et al., 2016b; Satchwell et al., 2015) rather than introducing more fundamental policy changes, such as market-based compensation (Couture and Gagnon, 2010; Wolak, 2013). Driven by the advent of socket parity[3] and critical levels of distributed solar PV in some geographies, policy makers in these frontrunner regions currently tend to promote "self-supply" over "grid-supply" systems by lowering the incentives for feeding electricity into the public grid. Since these amendments foster the deployment of smaller PV installations (*ceteris paribus*), they may help limit the impact of residential solar on the electricity infrastructure in the short term. However, these smaller systems fall short of reaping scale effects in the installation process (Barbose and Darghouth,

[1] "Avoided costs of solar PV" are commonly based on the average electricity wholesale daytime price, which is strongly driven by marginal costs of the incumbent generation infrastructure, i.e. largely or fully depreciated, conventional power plants.

[2] Examples of incremental FiR design changes include the introduction of separate compensation levels for "grid-supply and self-supply systems" (e.g. Hawaii, 2015), fixed "feed-in caps" (e.g. Germany, 2013), or incentives for "self-consumption" (e.g. Germany, 2009–2012) or "direct marketing" (e.g. Germany, 2014).

[3] Socket parity is reached once the levelized cost of energy from solar PV falls below the prevalent retail electricity rates (i.e. the price at the electricity socket) in a given geography (Hagerman et al., 2016).

2016; Gillingham et al., 2016), and impede prosumers[4] from addressing additional services in front of the meter (Fitzgerald et al., 2015). In addition, given the increased incentive to consume PV electricity onsite instead of feeding into the grid, residential homeowners may decide to invest in energy storage and, in the longer term, defect from the grid (Bronski et al., 2014). This scenario stands in sharp contrast to an alternative path towards a "transactive grid", which builds on the full integration of distributed energy resources (DER) (St John, 2013).

These considerations and trade-offs illustrate the need for a comprehensive analysis that informs policy makers about the policy levers that are at their disposal, and how their design affects the emerging domain of residential prosumers in a given context. So far, both theoretical and empirical studies have scrutinized alternative FiR schemes along a number of metrics, such as system prices (Gillingham et al., 2016; Seel et al., 2014), bill savings (Darghouth et al., 2011), return on investment (Jenner et al., 2013), internal rates of return (Lang et al., 2015), social welfare (Yamamoto, 2012), dynamic efficiency (Del Río, 2012), policy costs (Huenteler, 2014), or feedbacks loops (Darghouth et al., 2016b). However, despite these valuable insights, the literature currently lacks an overview of the "FiR design maze" that provides actionable guidance to policy makers across geographies (Carl et al., 2012; Grueneich and Carl, 2012). This paper therefore connects and extends the literature on NEM and rate[5] design in the United States and FiT in Europe (Comello and Reichelstein, 2016a; Poullikkas, 2013), and systematically examines how the key elements in FiR design, i.e. remuneration levels and feed-in constraints, affect the investment rationale of residential prosumers (Rickerson et al., 2014).

To do so, we employ a techno-economic model to derive the optimal, i.e. net present value (NPV) maximizing, PV installation size under both generic and real-word FiR schemes. This metric allows us to determine if residential PV investments are economic, and whether the system is designed for self-supply, grid-supply, or a combination thereof, which serves as a proxy for its impact on the electricity system. In a subsequent step, we introduce a framework that captures how FiR design, retail electricity rates, and levelized cost of electricity (LCOE) combine to affect the economics of residential PV. This framework is applicable across contexts and allows policy makers to gain an understanding of how their design choices shape the rationale of residential prosumers in terms of optimal PV system sizing and operation. To illustrate the applicability of our concept, we elaborate on the two most widely applied FiR instruments that policy makers are frequently referred to, namely NEM and FiT using input and PV installation data from California and Germany, respectively, between 2005 and 2016.

Our study holds valuable insights for policy makers and stakeholders affected by the emergence of residential solar PV. We find that the design of a particular feed-in remuneration scheme and its

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[4] For our study, we define "prosumers" as residential electricity end-consumers who employ a rooftop PV system to generate electricity for the purpose of direct onsite consumption (self-consumption) or export to the electricity grid (feed-in).

[5] In this article the notions "retail rates" and "retail electricity prices" are used synonymously.

interplay with retail rates and PV system costs jointly determine both the extent to which residential PV installations are economic as well as how they are sized (Couture and Cory, 2009; Seel et al., 2014). PV system sizes, in turn, essentially determine a) the energy autonomy of residential households, b) the disruptive potential for electric utilities, and c) the impact on grid stability and requirements for infrastructure upgrades. Policy makers should be aware of their influence on the size of residential solar PV systems and think about what role residential prosumers should adopt in an evolving electricity system. The support of larger system sizes involves trading-off reduced residential PV deployment costs and prosumer participation against increased complexity of PV system integration and stronger disruptive effects for utilities and grid operators. Last but not least, in order to avoid unintended consequences of FiR design, policy makers should transparently track the key indicators that affect residential solar PV economics, namely rate design and LCOE, and carefully weigh individual policy interventions against each other (Rogge and Reichardt, 2016).

The paper is structured as follows. Section 2 describes the techno-economic model, and the longitudinal input data from California and Germany. Section 3 illustrates how FiR design affects optimal residential PV sizes, and lays out the conceptual framework that captures how policy shapes the role of residential PV prosumer paradigms. Section 4 discusses implications for policy makers and the literature, and outlines the key limitations of our study, before Section 5 presents our conclusions.

2 Methodology and Data

To assess how feed-in remuneration (FiR) schemes affect residential PV sizes we follow a two-step approach. First, we model the effects of different FiR designs on the optimal size of residential solar PV systems. Second, we elaborate on the combined effects of FiR design, retail electricity rates, and PV system costs based on a conceptual framework that is applicable across various contexts.

2.1 Modeling the effect of FiR design on optimal residential PV sizes

To scrutinize how the key elements of FiR design affect residential PV sizes, we employ a techno-economic simulation toolset that was developed in previous work (Lang et al., 2016, 2015, 2013) and has been significantly extended for the purposes of the analysis at hand, while maintaining consistency with related literature (Christoforidis et al., 2016; Comello and Reichelstein, 2016a; Mondol et al., 2009; Poullikkas, 2013). In particular, we adopt the perspective of a residential homeowner who seeks to maximize the net present value (NPV) of a rooftop PV system with a lifetime T of 25 years by choosing the optimal PV installation size k^*.

$$k^* = \max_{k \in \{1,2\dots20\}\,[kW]} NPV(k) \qquad (1)$$

Given physical sizing constraints of real-world single-family houses, we exclude installation capacities larger than $20kW$. As outlined in Figure 1, the $NPV(k)$ and the subsequent choice of k^* depend on the household's PV supply and electricity demand profiles, which translate into three cash flows of the focal investment.

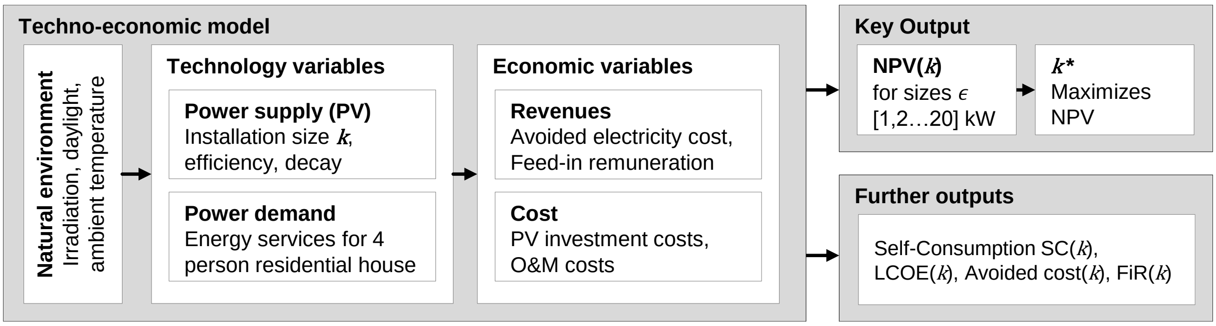

Figure 1: Conceptual outline of techno-economic model

Given in equation (2) are two revenue components, i.e. the avoided cost of electricity and the remuneration for electricity feed-in, and one cost component, i.e. the levelized capital and operational expenditures for the PV system (all in USD/kWh). The time value of money is captured by the discount factor $\gamma^i = 1/(1+r)^i$ for a given discount rate r.

$$NPV(k) = \sum_{i=1}^{T} \gamma^i \cdot \left[\sum_{t=1}^{8760} \left(AvoidedCost_i(t|k) + FiR_i(t|k) - LCOE(k) \right) \cdot E_{PVGen}(t|k) \right] \qquad (2)$$

The electricity bill savings[6] that arise from using a PV system of size k depend on the share of PV electricity that is directly "self-consumed" onsite $SC(t|k)$ (without unit), which avoids purchasing electricity from the grid at the going retail rate in year i, $p_{retail_i}(t)$ (in USD/kWh).

$$AvoidedCost_i(t|k) = SC(t|k) \cdot p_{retail_i}(t) \tag{3}$$

The share of electricity generation that remains, $1 - SC(t|k)$, may result in additional feed-in revenues at the going feed-in remuneration level in year i, $p_{FiR_i}(t|k, constraints)$ (in USD/kWh), under potential feed-in constraints that will be scrutinized below.

$$FiR_i(t|k) = \big(1 - SC(t|k)\big) \cdot p_{FiR_i}(t|k, constraints) \tag{4}$$

Adding the cost component of equation (2), the levelized cost of electricity[7] from a PV system with useful economic lifetime T can be denoted as (Reichelstein and Yorston, 2013):

$$LCOE_{net}(k) = \frac{SystemPrice_{net}(k) + \sum_{i=1}^{T} \gamma^i \cdot O\&M(k)}{\sum_{i=1}^{T}\left(\gamma^i \cdot k \cdot \int_t^{\cdot} P_{PVGen_{norm}}(j)\, dj\right)} \tag{5}$$

The system price outlined above represents the full turnkey capital cost to a residential solar PV investor, i.e. including hardware (e.g. PV panel, inverter, balance-of-system), soft costs (e.g. installation, interconnection), and a potential mark-up value. In cases where upfront support schemes – such as grants or tax credits – are available at the time of the investment, the gross value is deducted by the corresponding support level, which yields the net system price $SystemPrice_{net}(k)$. In line with previous literature, operation and maintenance costs ($O\&M$) accrue annually, and are incorporated as a fixed fraction of the gross system price (Lang et al., 2016; Weniger et al., 2014). In the standard setup, $SystemPrice_{net}$, $O\&M$, and hence $LCOE_{net}$, scale linearly with PV system size k, which means that the relative system price (in USD/W) is flat. As part of the additional results (cf. Appendix), we have also included a non-linear option that reflects economies of scale.

The absolute hourly cash flow (in USD) in equation (2) is derived by multiplying the relative values from equations (3), (4), and (5) by the electricity generated by the solar PV system in the corresponding hour, $E_{PVGen}(t|k)$. The normalized, quarter-hourly yield of a PV system $P_{PVGen\_norm}(j)$ (in kWh/kW_{peak}) is determined by the horizontal irradiation ($Irrad$), the panel area (A), the rooftop tilt factor (θ), and the actual cell efficiency (η) being affected by daylight and ambient temperature, as well as a number of conversion losses on the system (τ_{system}) and inverter ($\tau_{inverter}$) level.

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[6] In this analysis, we deliberately abstract from the additional revenue that accrues from "tiered" rate structures, i.e. the lower average retail rate that households can achieve by investing in a PV system that lowers the residual electricity demand from the grid.

[7] Throughout our study the abbreviation LCOE refers to $LCOE_{net}$.

$$P_{PVGen\_norm}(j) = Irrad_{j} \cdot A \cdot \theta \cdot \eta_j \cdot \left(1 - \tau_{system}\right) \cdot (1 - \tau_{inverter}) \quad (6)$$

Our PV system simulation module incorporates global data for one meteorological year and is very much in line with the approach pursued in NREL's PVWatts tool (Dobos, 2014). Assuming that the power output of the PV system scales linearly with the installation size, the quarter-hourly supply profile of a system of size k is given by $P_{PVGen}(j|k) = k \cdot P_{PVGen\_norm}(j)$ (in kW), and its yield in hour t defined as $E_{PVGen}(t|k) = \int_t P_{PVGen}(j|k)\, dj$ (in kWh). To render the quarter-hourly electric load profile $P_{Load}(j)$, our model uses a bottom-up approach[8] that incorporates the location-specific energy service demands (e.g. air conditioning, cooking, washing) of a single family household with four residents (Lang et al., 2016). As a complement to the absolute PV system size, we introduce the $PV/Load$ ratio (without unit) in order to increase the transferability of our results beyond the two focal geographies[9].

$$PV/Load = k \cdot \frac{\sum_{t=1}^{8760} E_{PVGen\_norm}(t)}{\sum_{t=1}^{8760} E_{Load}(t)} \quad (7)$$

For each hour t of the year, a quarter-hourly dispatch (running from $j = 4(t-1)+1$ to $4(t-1)+4$) determines how much of the energy produced by the PV system is used to directly meet the onsite electricity demand of the corresponding residential building (Beck et al., 2016):

$$E_{PV2House}(t|k) = \begin{cases} \sum_{j=4(t-1)+1}^{4(t-1)+4} {}^{1}\!/_{4}\,\mathrm{h} \cdot \min \{P_{Load}(j), P_{PVGen}(j|k)\}, & p_{retail_i}(t) \geq p_{FiR_i}(t|k, constr) \\ 0 & , \quad else \end{cases} \quad (8)$$

The dispatch logic is therefore as follows: When the electricity retail rate, $p_{retail_i}(t)$, lies above the going level of feed-in remuneration, $p_{FiR_i}(t|k, constr)$, the PV generation, $P_{PVGen}(j|k)$, is used for self-supply – unless it exceeds the household's current electric load, $P_{Load}(j)$. When this is not the case, no electricity is consumed onsite. Therefore, assuming no losses, the energy being fed into the

[8] This setup provides us with full control over the input parameters and thereby grants methodological consistency across different contexts. Seasonal aggregates of the load and demand profiles for the focal geographies of this study are provided in the Appendix.

[9] The annual electricity demand of residential consumers may vary greatly between different regions, countries, and customer segments (Kwac et al., 2014; Tjaden et al., 2016), which translates into a wide range of cost saving potentials by rooftop PV systems. The $PV/Load$ ratio allows us to attenuate this aspect.

grid can be denoted as $E_{PV2Grid}(t|k) = E_{PV2Gen}(t|k) - E_{PV2House}(t|k)$. Based on the rationale outlined in (8), we can express the hourly share of self-consumption $SC(t|k)$ as

$$SC(t|k) = E_{PV2House}(t|k) \,/\, E_{PVGen}(t|k) \qquad (9)$$

Correspondingly, as long as no limitations for PV electricity feed-in exist, the hourly feed-in share is given by $FI(t|k) = 1 - SC(t|k)$. To conveniently compare a range of different FiR schemes, we distinguish between the *level and temporal pattern of remuneration* from a set of potential *feed-in constraints*, both of which are captured in our focal FiR design variable $p_{FiR_i}(t|constr)$. Two examples for the interaction between feed-in levels and constraints are provided in Figure A.3 in the Appendix.

Table 1: Overview of FiR design elements implemented in the techno-economic model

FiR design element	Parameter	Examples Net Metering (California 2016)	 Feed-in Tariff (Germany 2016)	 Alternative Approaches
FiR level & pattern	$p_{FiR}(t\|constr)$:			
Fix vs time-variant	"	Fix[1]	Fix	Market premium
Tied to retail	"	Retail rate	Fixed tariff	Fraction of retail rate
Tied to wholesale	"	Average 7am–5pm	Avoided cost	Daily average
Constraints	$constr$:			
System size	$k_{threshold}$	1MW	10kW, 40kW	Plant size threshold
Feed-in, Power	$P_{threshold}$	No constraint	No constraint	Feed-in cap
Feed-in, Energy	$E_{threshold}$	Resid. Consumpt.	90% of E_{PVGen}	Non-negative bill
Eligibility period	T_{FiR}	20 years	20 years	10 years

[1] At the time this analysis was conducted, the NEM program cap in PG&E's service territory (2,409MW, cf. Assembly Bill 327) was not yet reached. Accordingly, the values above reflect the original 'NEM 1.0' program and do not capture the changes associated with the NEM Successor Program ('NEM 2.0') (CPUC, 2015; St John, 2016).

The main building blocks of a given FiR design are outlined in Table 1, which is based on an extensive literature review[10] of numerous FiR schemes (e.g. Net Billing, Feed-in Premiums, Contracts for Difference) that are currently in place or under discussion. To show the applicability of our taxonomy we have outlined two of the most widely applied FiR support schemes for residential solar PV, namely

[10] To concentrate on the actual effect of different FiR designs on PV sizing and prosumer paradigms, this study deliberately abstracts from certain "soft" aspects of FiR schemes, such as their ease of implementation, or associated initiatives, such as streamlined interconnection procedures for PV systems. In addition, we do not look into potential higher-level policy strategies, such as deployment goals that govern e.g. the subsequent step-down in FiR levels.

NEM and FiT, as currently implemented in California (CA/PG&E[11]) and Germany (DE) respectively. By specifying the constraint parameters $k_{threshold}$, $P_{threshold}$, $E_{threshold}$, and T_{FiR}, our simulation toolset allows us to incorporate a diverse set of present and future feed-in remuneration designs that set the shape and level of our focal variable $p_{FiR_i}(t|k, constraints)$ (cf. section 3.1).

2.1.1 Data for FiR design analysis

To assess the impact of FiR design on NPV-optimal sizing of residential solar PV systems (cf. section 3.1), we elaborate on four FiR designs (p_{FiR_i}) that are characterized by the parameters outlined in Table 2, columns a) to d). The first two FiR designs can be regarded as generic equivalents of a Net Metering and a Feed-in Tariff policy. The third FiR design represents a hybrid of the former, while the fourth is used to model the absence of feed-in remuneration. The remaining techno-economic parameters, cf. lines 'Supply & Demand' and 'Economic', represent a blend of data from California and Germany around 2012 and have been selected for illustrative purposes. They are kept constant throughout the FiR design analysis. As outlined in the previous section, the PV generation[12] and electricity demand profiles are generated within the techno-economic model based on the approach by Lang et al. (2015, 2013) and correspond to a household located in San Francisco. Their patterns are shown in Figures A.1 and A.2. To test the robustness of our findings on the impact of alternative FiR designs to changes in the otherwise constant input parameters, we conducted a series of sensitivity analyses, including different load profiles, solar irradiation levels, additional electricity price and feed-in patterns, as well as scale effects in system prices. The results of these sensitivities are shown in Figures A.4 and A.5 along with their corresponding inputs.

[11] The values for California represent the current status of the NEM scheme in the electric utility service area of Pacific Gas and Electric (PG&E).

[12] Detailed technical input data for the simulation of residential PV in California and Germany is provided in Table A.1.

Following the taxonomy provided by Table 1, in designs a) – c) we subsequently vary feed-in constraint 1, remuneration level 1, and remuneration level 2, each along three particular options indicated as i), ii), and iii). To elaborate on the effect of these variations in FiR design in isolation, the remaining techno-economic input parameters (cf. rows "Supply & Demand", and "Economic" in Table 2) are fixed.

Table 2: Input data for the FiR design analysis

	a) NEM scheme	b) FiT scheme	c) Hybrid scheme	d) no Feed-in
FiR level 1	i) 1.00x p_{retail_i} ii) 0.75x p_{retail_i} iii) 0.50x p_{retail_i} Steady increase	i) 1.25x p_{retail_1} ii) 1.00x p_{retail_1} iii) 0.75x p_{retail_1} No increase	As in scheme b)	0 ct/kWh
FiR constraint 1	Feed-in, energy $E_{threshold}$: Residual consumption	System size $k_{threshold}$: PV/Load = 1	As in scheme a)	-
FiR level 2	NSCR=3.50ct/kWh	0.9x FiR level1	i) 2.0xLCOE ii) 1.5x LCOE iii) 1.0x LCOE	0 ct/kWh
FiR constraint 2	T_{FiR}: 20y			T_{FiR}: 25y
FiR level 3	2.50ct/kWh			-
Supply & Demand	Annual PV generation [1]: 1,570kWh/(kW·y) Annual electricity demand [2]: 7,000kWh/y			
Economic	$p_{retail_1} = 28.74$ct/kWh $p_{retail_i} = p_{retail_1} * 1.015^{i-1}$ $SystemPrice_{net} = 2{,}810\$/kW$ $T = 25$ years			
	$r = 3.5\%$			i) $r = 3.5\%$ ii) $r = 6.0\%$ iii) $r = 8.5\%$

[1] cf. Figure A.1a); [2] cf. Figure A.2a)

2.2 Illustrating the integrated effect of policy on optimal residential PV sizes

In the second part of our analysis (cf. section 3.2), we look at the combined effect of FiR design, electricity rates, and system costs on the optimal installation size k^*. To do so, we extract the middle section[13] of the NPV formulated in equation (2), insert equations (3) and (4), and divide this term by $LCOE$ (> 0). This can be framed as the hourly benefit-to-cost ratio (BCR) of a rooftop PV system of size k:

$$\left(\frac{SC(t|k) \cdot p_{retail_i}(t)}{LCOE(k)} + \frac{(1 - SC(t|k)) \cdot p_{FiR_i}(t|k, constr)}{LCOE(k)} - 1\right) = BCR(t|k) - 1 \qquad (10)$$

This dimensionless variable can be seen as an indicator of whether a given PV system of size k is economic for a given combination of FiR design, electricity rates, and system costs. In particular, $BCR(t|k) > 1$ if at least one of the two revenue-to-cost ratios is larger than 1, given that both rate and feed-in remuneration are positive. That means that if either one of the first two numerators, namely the levelized rate p_{retail_lev} or the levelized feed-in remuneration p_{FiR_lev}, exceeds the levelized cost, investing into a residential PV system is economic. If both ratios are smaller than 1, it follows that $BCR(t|k) < 1$, which means that a residential solar PV investment is uneconomic from both the perspectives of avoiding electricity cost and selling electricity to the grid. To illustrate the latter let us assume that $p_{retail_i} = p_{FiR_i} < LCOE$. In this case, $BCR(t|k)$ in equation (10) becomes independent of the self-consumption share $SC(t|k)$ and reduces to $p_{retail_i}/LCOE$, which we know is smaller than 1 given our previous assumption $p_{retail_i} < LCOE$. The same holds true for any other choice: $p_{retail_i} < p_{FiR_i} < LCOE$ or $p_{FiR_i} < p_{retail_i} < LCOE$ (■).

In the following we will reframe this approach as a heuristic that renders it easier to apply by other researchers, policy makers or analysts. In particular, since deriving the levelized rate p_{retail_lev} and the levelized feed-in remuneration p_{FiR_lev} is associated to a certain computational effort, it may make sense to look at daily averages of the electricity prices and feed-in remuneration in the first year of the investment (p_{retail_1}, p_{FiR_1}). This is particularly simple in case the level of electricity prices and feed-in remuneration are fixed, or if they underlie a regular temporal pattern. On this basis, we can look at the 'year 1 benefit-to-cost ratio' and draw similar conclusions in terms of the economics of the PV investment as for the generalized approach above, as long as we assume that weighted[14] average of electricity prices and feed-in remuneration levels remains above the level of $LCOE$ in future years. This heuristic is introduced in detail as part of an analytical framework in section 3.2.1, and subsequently applied to empirical data from California and Germany in section 3.2.2.

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[13] "$AvoidedCost_i(t|k) + FiR_i(t|k) - LCOE(k)$"

[14] As expressed in equation (10), this refers to the weights by the the hourly self-consumption (SC), and feed-in level ($1 - SC$) respectively.

2.2.1 Data for integrated policy analysis

To assess the combined impact of FiR design, electricity rates, and system costs on NPV-optimal sizing of residential solar PV systems (cf. section 3.2), we elaborate on empirical data from the state of California and the federal state of Germany between 2005 and 2016 that is outlined in Table 3. This data is retrieved from a number of different sources, including government agencies, research institutes, and industry associations active in the distributed solar PV domain in California and Germany.

Table 3: Economic input data for the empirical policy analysis (all values for year i=1)

	California (Full Net Metering, CSI) [1]			Germany (Feed-in Tariff) [2]		
Parameter	p_{retail_i}	$p_{FiR_i} = p_{retail_i}$	$SystemPrice$ [3]	p_{retail_i}	$p_{FiR_i} = FiT$	$SystemPrice_{net}$ [3]
Unit	ct/kWh	ct/kWh	Gross | Net $/W	ct/kWh	ct/kWh	$/W
2005	17.8	17.8	9.4 | 4.5	20.7	60.5	8.2
2006	21.3	21.3	9.3 | 4.6	21.6	57.5	8.0
2007	22.9	22.9	9.2 | 4.7	22.9	54.6	7.0
2008	22.2	22.2	9.0 | 4.9	24.0	51.9	6.2
2009	24.7	24.7	7.4 | 4.1	25.8	47.7	5.8
2010	27.6	27.6	6.4 | 3.8	26.3	43.5	4.4
2011	28.0	28.0	5.9 | 3.7	28.0	31.9	3.7
2012	29.5	29.5	5.1 | 3.4	28.7	27.1	2.8
2013	30.0	30.0	4.7 | 3.2	32.0	18.9	1.9
2014	32.4	32.4	4.4 | 2.9	32.4	15.2	1.7
2015	27.3	27.3	4.0 | 2.8	32.0	13.9	1.6
2016	27.4	27.4	3.4 | 2.4	32.0	13.7	1.6
Source	El. rate E-1, Tier 3 (PG&E)	NEM Program website (IOUs and CPUC)	Tracking the Sun (LBNL); CSI & ITC websites	El. consumption in households report (BDEW)	FiT Program website (BNetzA)	Recent facts on PV report (Fraunhofer ISE)

In addition, we complement the longitudinal analysis of the policy impact on solar PV economics in California and Germany with deployment data between 2005 and 2016 (cf. Table 4). To do so, we draw on two publicly available sources, namely the "Currently Interconnected" database on PV systems in California, which is maintained by the administrators of the California Solar Initiative (CSI), and the register of PV plants in Germany, which is a subset of the larger "Renewable installations register" maintained by Germany's federal grid agency (BNetzA). Both sources provide sufficiently high temporal (daily) and installation size (two digit) resolution for the purpose of the analysis at hand. Since entries in the German database are not explicitly categorized according to customer segments, we have focused on small-scale PV installations with $k \leq 20kW$.

Table 4: Sources of residential solar PV deployment data for California and Germany

	California	Germany
Database	CSI - Currently Interconnected	Renewable installations register
Provider(s)	CSI program administrators, CPUC	BNetzA, four German TSOs
Imported categories	Approved date, size (DC/AC), incentive (type/level) (total: 123 categories)	Date installed, size (AC), feed-in cap (total: 15 categories)
Temporal scope	1993–2016	1984–2016
Policy info	CSI, ITC, NEM	Implicit[1]
Filters applied		
Technology	Solar PV	Solar (El. grid connected -> PV)
Temporal scope	2005–2015	2005–2015
Segment	Residential	Not specified
Extracted inst. sizes	0-20 kW	0-20 kW
Final sample size	422,048	1,098,838
Capacity of final sample	2,164 MW	9,131 MW

[1] The data entry is required for all systems enrolled in the FIT program (cf. “Renewable Energy Act”)

3 Results and Discussion

3.1 How FiR design affects optimal PV sizes

In the following results, we show how FiR affects the economics of residential solar PV (NPV) and the sizing rationale of the corresponding investors (k^*, $PV/Load^*$, SC^*). To do so, we simulate how different feed-in remuneration designs affect optimal installation sizes for residential PV systems based on a selection of FiR design elements introduced in section 2.1.

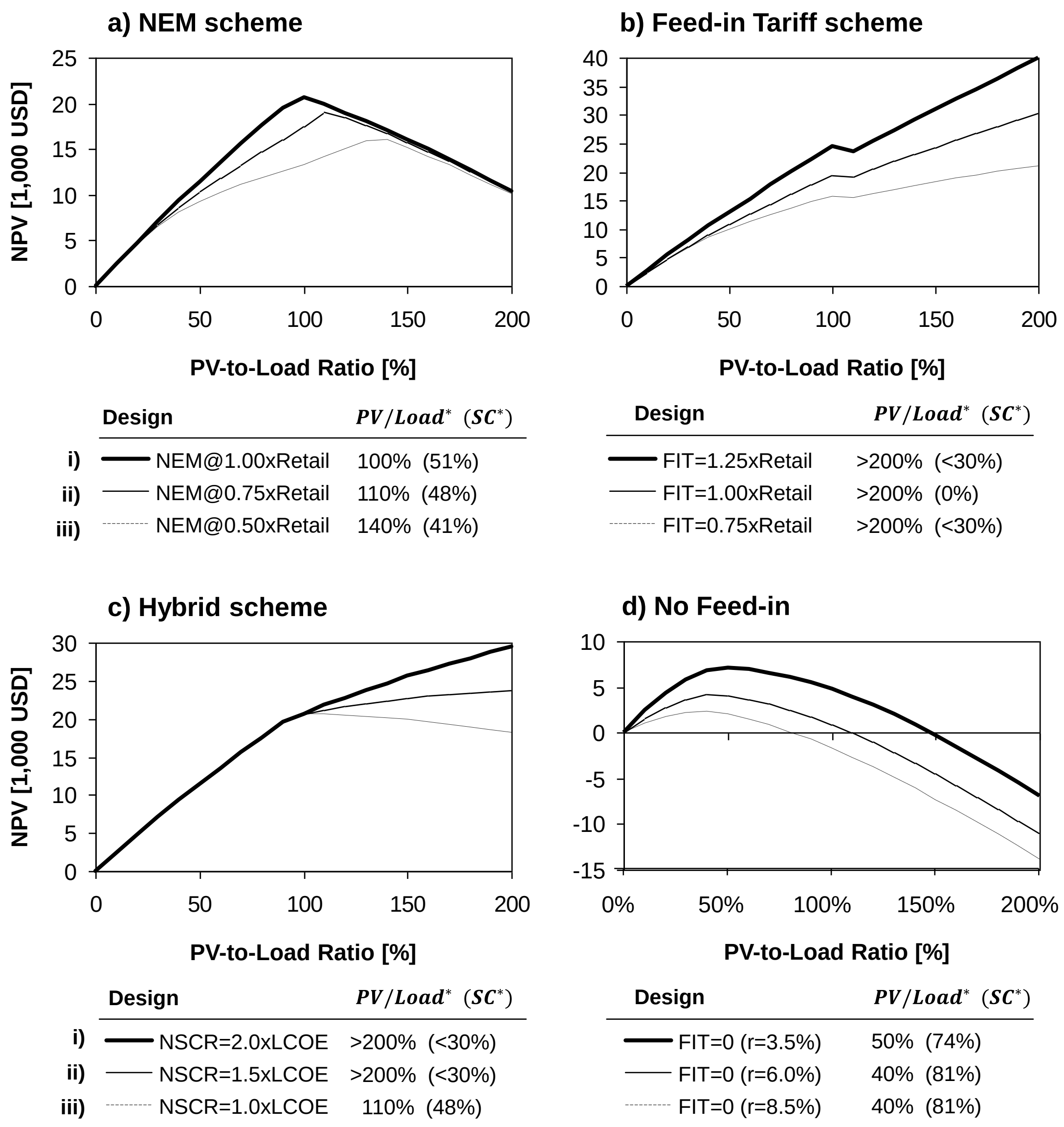

Figure 2: The effect of FiR design on residential solar PV sizes

We look at three exemplary FiR archetypes in particular, namely a NEM scheme, a FiT scheme, and a scheme that can be regarded as a hybrid of the first two. Additionally, we display how the absence of feed-in remuneration affects the economics of the focal investment. As outlined in Figure 2, we find that the NPV maximizing sizes differ significantly, both across the archetypical FiR schemes a) to c) and the characteristics on the design level (i – iii). In the following we scrutinize the drivers behind these differences.

Within the NEM scheme (Figure 2a), we first look at design a-i), which corresponds to "full" Net Metering, i.e. feed-in is compensated at the going retail electricity rate. We find that under this scheme the NPV maximizing $PV/Load$ ratio lies at $PV/Load^{*} = 100\%$ ($k^{*} = 4.5kW$), which means that it is economic to install a system that is sized to cover the total annual electricity demand of the residential household. This is also reflected in the self-consumption rate $SC^{*} = 51\%$, which indicates that almost half of the annual PV electricity supply is fed into the grid. Installing a smaller system would mean that the household wouldn't be taking advantage of other revenue opportunities from additional bill savings or feed-in. Installing a larger system, in turn, means that annual feed-in exceeds the total residual amount of electricity that is drawn from the grid, with the excess feed-in being compensated at the going Net Surplus Compensation Rate (NSCR) at the end of each year. Since the NSCR lies below the levelized cost of electricity for the focal PV investment, it makes no economic sense to expand the PV capacity beyond the threshold of $PV/Load^{*} = 100\%$. In other words, the additional investment cost to extend the system would exceed the additional gains to be reaped through higher production. However, the logic changes when lowering the FiR level and deviating from "full NEM". As designs a-ii) and a-iii) show, the optimal PV size increases to $PV/Load^{*} = 110\%$ (a-ii) or 140% (a-iii) when lowering the value of "electricity bill credits" by $1/4$ of the retail rate in a-ii and by $1/2$ of the retail rate in a-iii. In doing so, the household trades off a higher feed-in share ($1 - SC^{*} = 52\%$ for a-ii, and $1 - SC^{*} = 59\%$ for a-iii) – and thereby a larger amount of feed-in credits that still significantly exceed PV generation costs in both designs – against an increasing amount of electricity that is compensated at the NSC rate, which falls below generation costs. To counteract the "lower" value of each kWh that is fed into the grid (when compared to "full NEM"), more PV electricity must be fed into the grid in order to build up feed-in credits that can be used to offset electricity bills in subsequent months.

Under any of the three Feed-in Tariff designs illustrated in Figure 2b, a NPV-maximizing investor would opt for the largest PV system that could be installed on a given rooftop. This holds true independent of the capacity constraint set at $PV/Load = 100\%$, which results in a dip[15] in the NPV beyond this threshold. The specific slope of $NPV(k)$ depends on the feed-in remuneration level that

[15] Please note that in real-world FiT schemes, such as in Germany, this dip does not occur because the tariff for an 11kW installation, for example, is a proportional composition of the tariffs before and beyond the threshold, i.e. $p_{FiR}(k = 11kW) = 10/11 \cdot p_{FiR}(k \leq 10kW) + 1/11 \cdot p_{FiR}(k > 10kW)$.

is set at b-i), the retail electricity price level, b-ii), 25% above, or b-iii), 25% below. Given the high level of feed-in remuneration in design b-ii), which exceeds the going retail rate at least in the first 15 years of the investment (recall that we assume an annual rate increase of 1.5%), a household would feed-in all the production into the public grid rather than self-consuming PV electricity onsite ($SC = 0\%$).

Addressing the observation by Couture et al. (2015, p. 19) that "policymakers are beginning to respond by developing policies that lie somewhere between traditional net metering and feed-in tariffs", Figure 2c presents a hybrid of the first two FiR designs. The key difference between design c) and NEM scheme a-i) is that the NSCR is set at variations of the levelized cost of electricity ($LCOE_{net}$) rather than at the average wholesale price level of the previous year. This renders the NSCR to be about three times higher in c-i) than in a-i), which means that the installation of a larger system is more attractive ($PV/Load > 200\%$). While the same holds true for c-ii), under design c-iii) we observe that the optimal power-to-load ratio reverts back to a level near "full NEM" as in design a-i), i.e. $PV/Load^* = 110\%$. Last but not least, in the case of no feed-in remuneration being paid (cf. Figure 2d), we find that the NPV of an optimally sized PV system drops significantly. Therefore, extending the installation size beyond a certain threshold, in this case $PV/Load^* = 50\%$ (or 40% for higher discount rates), makes no economic sense. While our setup is characterized by a relatively high spread between electricity rates and PV $LCOE$, it can be assumed that, to date, the absence of feed-in remuneration would render residential solar PV systems uneconomic in most geographies[16], especially for higher discount rates (cf. d-i) vs d-iii)).

Our analysis reveals that FiR design, i.e. the specification of *remuneration levels* and *feed-in constraints*, can be regarded as a versatile and important toolbox that allows policy makers to govern the role residential PV systems might play in future electricity grids. Since our examination of FiR designs assumed a fixed "post socket parity" setting with a particular retail rate and particular PV costs, it only represents a small fraction of the potential real-world scenarios. For this reason, we relax these assumptions in the next part of the analysis.

[16] Detailed sensitivity analyses are provided in the Appendix.

3.2 How policy shapes the role of residential solar PV

3.2.1 Framework: The drivers behind residential solar PV paradigms

As indicated above, feed-in remuneration (p_{FiR}), electricity rates (p_{retail}), and levelized cost ($LCOE_{net}$) combine to shape the optimal investment size of a residential solar PV system. To allow policy makers and stakeholders to easily navigate these drivers from an integrated perspective, we introduce a stylized decision-making framework that can be applied across empirical contexts.

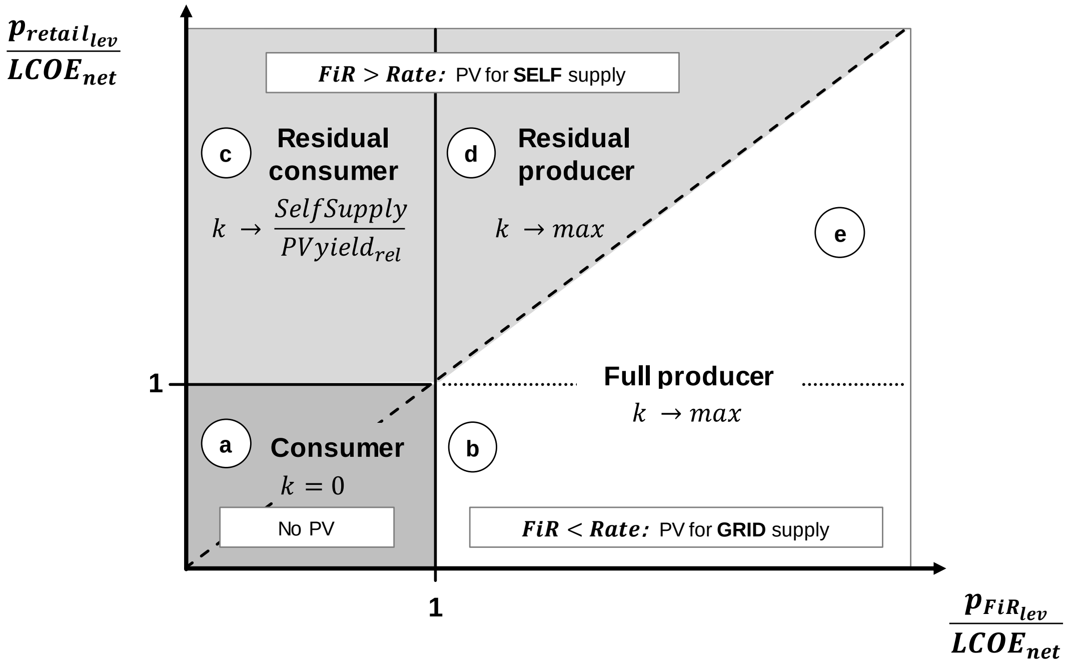

Figure 3: Framework: The drivers of residential PV paradigms

In Figure 3 we map any given combination of the two components of the simplified benefit-to-cost ratio (cf. section 2.2), namely retail rate and feed-in remuneration levels, to a corresponding estimate for the optimal PV installation size k^* and an end consumer paradigm. The lower left-hand corner (cf. area a) depicts a case in which both feed-in remuneration (FiR) and the going retail rate are below $LCOE_{net}$ (both ratios < 1), i.e. investing in solar PV is uneconomic. We frame this base scenario as the "consumer" case. Moving one field to the right (a->b), the situation changes because the levelized compensation for exporting PV electricity into the grid now exceeds the levelized cost of electricity provided by the rooftop PV system ($p_{FiR_{lev}} > LCOE_{net}$, i.e. $p_{FiR_{lev}}/LCOE_{net} > 1$). In the case where no additional feed-in constraints exist, a rational investor would then opt for the maximum installation size possible given physical (rooftop size) constraints ($k \rightarrow max$), and export all of the energy produced by the rooftop PV installation to the grid, thereby becoming a "full producer".

Focusing on the upper left quadrant (cf. area c), we find a situation in which the retail electricity rate exceeds LCOE while the compensation for electricity feed-in does not ($p_{retail_{lev}} > LCOE_{net} \wedge p_{FiR_{lev}} < LCOE_{net}$). In other words, producing electricity to avoid paying retail rates is attractive but selling it to the grid results in a loss. In this case, we expect that a residential household is faced with a trade-off in sizing its solar PV installation. The optimal size is reached when the marginal return of expanding the installation size by an increment of size k' (the marginal cost of electricity that is additionally avoided by k') is equal to the marginal loss of feeding more electricity into the grid. While it may appear economically attractive to supply a significant share of the household's electricity through a PV system, e.g. 26% in FiR design d-i) in the previous section, it is unlikely that this "load defection rationale" (Bronski et al., 2015) would spur households to completely defect from the electricity grid[17]. Accordingly, we deem this case the "residual consumer" in reference to the residual load that remains on the line. In the final case, i.e. the upper right areas d) and e) in Figure 3, the residential household faces economically attractive conditions for both load defection and PV exports to the grid. While this means that the PV installation should be as large as possible (cf. rationale of the "full producer"), the question of how the PV system is operated depends on the relative economic attractiveness of the retail rate vis-à-vis the level of feed-in remuneration. In the case of the retail rate exceeding feed-in remuneration, Figure 3d), the consumer would use the PV system to crowd out as much electricity consumption from the grid as possible and only export the residual electricity to the grid, thereby becoming a "residual producer". In the opposing case, Figure 3e), the PV owner would opt to sell the entire electricity production to the grid, in effect becoming a "full producer". Even though these two cases may seem similar when it comes to the physical PV system installed, the key difference lies in the fact that the entire electricity load of the "full producer" would still be billed by the utility company, just like a regular consumer who does not possess a PV system. Therefore, in contrast to the "full producer", a "residual producer" faces a lower electricity bill and, all things being equal, participates less in sharing the costs that arise from maintaining the public electricity infrastructure.

It seems reasonable to assume that each of the "prosumer" roles outlined above (residual consumer, residual producer, full producer) requires individual approaches when it comes to integrating them into the electricity system. Therefore, the framework above may be used by all entities involved in grid planning and operation (policy makers, regulators, utilities, grid operators) to track *ex ante* which role residential solar PV operators are likely to adopt under a given setup of $p_{FiR_{lev}}$, $p_{rate_{lev}}$, and $LCOE_{net}$. For example, a load defection scenario in which most of the residential PV owners become "residual consumers", and use their systems for self-consumption maximization, would be fundamentally different from an emerging paradigm of "full producers". Specific policy interventions, such as the shift to market-based feed-in remuneration, would become important much faster in the

[17] To be precise, this would only occur in the case of a household's demand pattern perfectly matching the PV generation profile throughout the entire investment time frame, a setting that is only realistic in the presence of advanced demand side management and energy storage technologies.

case of "full producers" than in the case of "residual consumers" (cf. the "self-supply" vs "grid supply" dichotomy in Hawaii (Trabish, 2015)). Recognizing that the frontiers between the individual customer paradigms can be framed as tipping points for residential solar PV, policy makers should track both their focal policy instruments (e.g. feed-in design, upfront support schemes) as well as further key variables along the grid edge, most importantly retail electricity rates, PV system prices, and load profiles, for different consumer segments.

3.2.2 Residential solar PV in California and Germany

To illustrate the applicability of our framework in a dynamic sense, we elaborate on the development of residential solar PV in California and Germany between 2005 and 2016. For both geographies, Figure 4 shows a scatter plot of the feed-in remuneration levels and the electricity rates as multiples of the net levelized costs in the first year of a small-scale[18] residential solar investment (for details cf. Tables 3 and A.2). We find that while California and Germany have both become attractive environments for residential solar PV investors ($p_{retail_1}/LCOE_{net} > 1 \wedge p_{FiR_1}/LCOE_{net} > 1$), the drivers behind this development differ significantly and diverge over time.

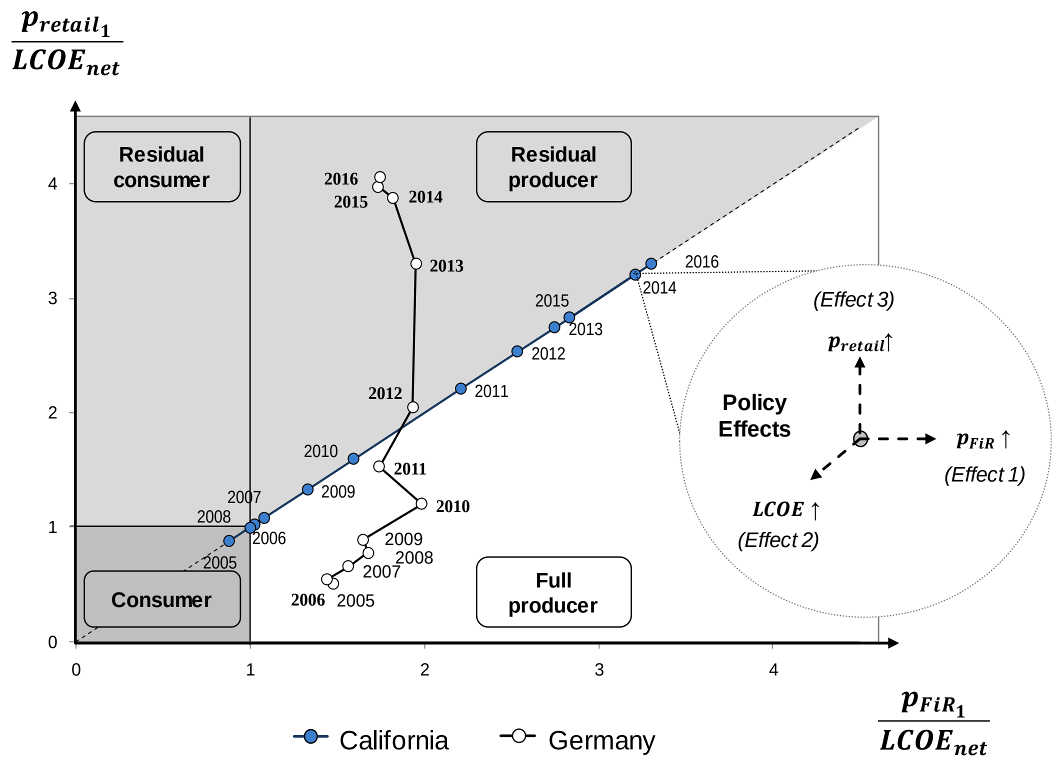

Figure 4: Policy trajectories in California and Germany, 2005–2016

[18] In particular, we assume that the PV system is sized small enough not to "violate" the corresponding feed-in constraint of the NEM ($E_{threshold}$) and the FiT scheme ($k_{threshold}$) (details provided in Table A.2), which would lead to a lower level of feed-in remuneration.

Policy makers in Germany opted for a constant support via a Feed-in Tariff (FiT) scheme that included dedicated design elements for small-scale solar PV systems. By contrast, residential solar economics in California were mostly driven by upfront grants from the state[19] and tax credits plus accelerated depreciation on the federal level[20] until about 2008 when the NEM scheme started to become increasingly important. While investment costs for residential solar PV systems have fallen and retail electricity rates have increased at a similar pace in both geographies (which explains the move along the vertical axis), the level of feed-in remuneration increased in California while it decreased in Germany. A closer look at the $p_{FiR_1}/LCOE_{net}$ ratio in recent years reveals that the German Feed-in Tariff tends to converge with the levelized cost of solar ($p_{FiR_1}/LCOE_{net} \rightarrow 1$), whereas the compensation under NEM in California is tied to the retail electricity rate and thus becomes increasingly decoupled from the underlying costs of solar ($p_{FiR_1}/LCOE_{net} \rightarrow 4$).

Recalling the framework in Figure 3, we expect that these differences in policy design have significantly affected residential solar economics and prosumer paradigms in both geographies. In particular, we estimate that until about 2012 a typical residential PV investor in Germany had opted for the role of "full producer", and since then has become a "residual producer", a shift that is likely to be reflected in a drop in optimal PV system sizes for a given residential household. In contrast, homeowners in California would have optimized their systems following the rationale of a "residual producer" with the assumption that they would continuously ensure not to violate[21] the feed-in constraint associated with NEM (i.e. the annual PV production may not exceed the annual demand).

To test whether the study of the trajectories in Figure 4 provides insight into the actual, real-world deployment of residential solar PV, we compare our results to installation data from California and Germany between 2005 and 2015[22].

[19] Cf. "California Solar Initiative" (CSI) (Borenstein, 2015b; Lacey, 2014).
[20] Cf. "Residential Renewable Energy Tax Credit", or in short, "Investment Tax Credit" (ITC) (Comello and Reichelstein, 2016b).
[21] For illustrative purposes, we did not explicitly capture this violation in Figure 4, although it would be possible to illustrate the decreasing feed-in level of "oversized systems" by a gradual move along the horizontal axis.
[22] At the time this paper was written, a complete dataset for 2016 was not yet available. However, the focal time frame 2005–2015 captures 98% of the residential PV deployment in California and 95% the of distributed PV deployment in Germany.

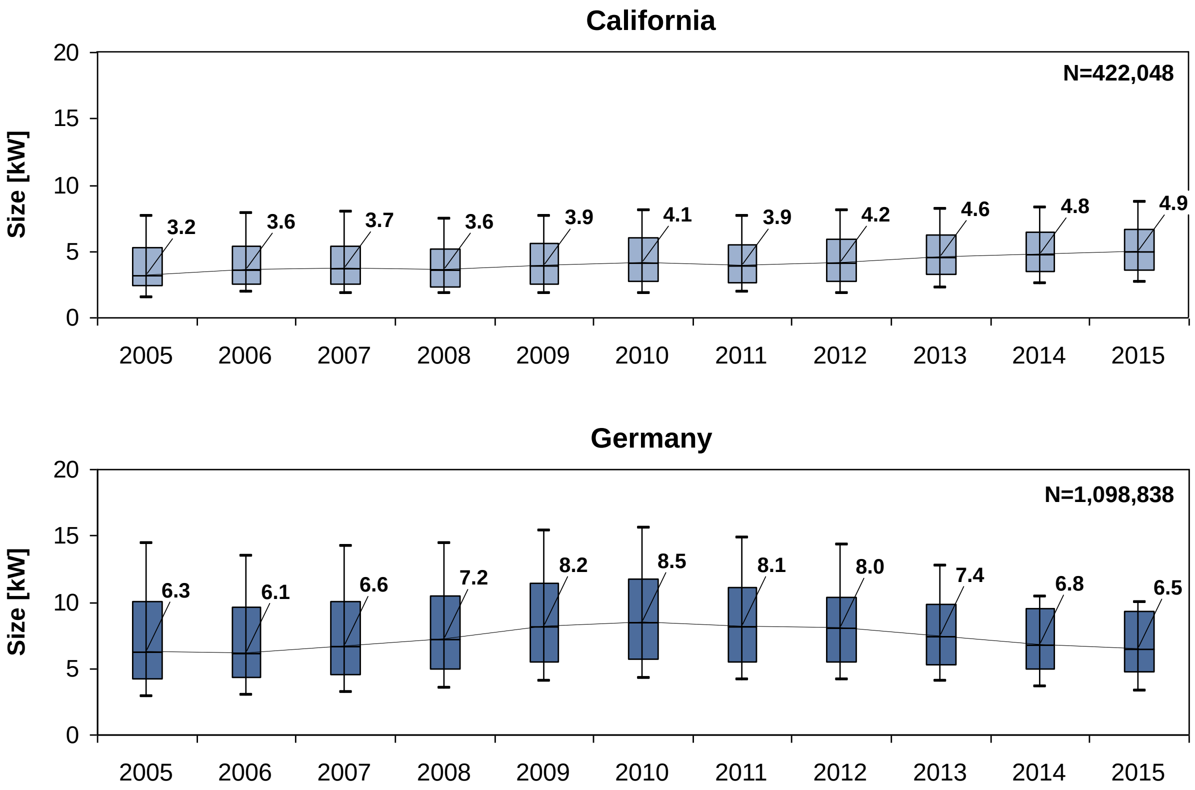

Figure 5: Distributed solar PV deployment in California and Germany; boxplots illustrate 10th, 25th, 50th, 75th, and 90th percentiles of residential (CA) and distributed (DE) PV installation sizes with a maximum capacity of 20kW

Figure 5 shows that the distribution of residential solar PV installation sizes differs significantly, both across the two focal geographies and over time. In fact, the median solar PV installation turns out to be consistently larger in Germany than in California, between 30% larger in 2015 and 109% larger in 2009 and 2011. The same holds true for the tails of the distribution, i.e. systems in the 10th and 90th percentiles (between 15% and 129% larger in Germany). This aggregate finding is in line with the expectation derived in the previous section with regards to the impact of Net Metering and Feed-in Tariffs on residential solar PV sizes. Looking at the temporal pattern within each geography, we find that the medium system size in California has continuously increased throughout our focal time period, namely from $3.2kW$ in 2005 to $4.9kW$ in 2015, with the exception of two minor drops in 2008 and 2011. This development may be explained by the fact that California's NEM regime only introduced the "Net Surplus Compensation Rate" (NSCR) as compensation for excess electricity in 2011 (cf. Assembly Bill 920, 2009). Hence, while the NEM scheme promoted a growing number of "residual producers" who optimized their PV systems for self-supply, the "penalty" associated with the production of surplus feed-in shrunk slightly over time. An alternative explanation could be the increasing share of BTM PV systems owned by third parties after 2009, which strongly professionalized the entire process of "system design and engineering, financing, and full installation"

(Drabkin et al., 2015, p. 2). This stands in clear contrast to Germany, where the medium installation size peaked in 2010 ($8.5kW$) after a more or less steady increase since 2005.

In addition to the insights gained from Figure 4, an interview with an expert in renewable energy finance revealed that there was a tipping point in the economics of residential solar PV in Germany around 2012, i.e. the year of "socket parity". Until then, a residential PV system was regarded as pure "income property", which meant that a surge of "full producers" had installed the largest PV systems possible given the size of their rooftop. Because of the affluence of German households, and the fact that banks were happy to support investments with such an attractive risk/return profile, there was no bottleneck in either equity or debt financing. As a result, for the longest time the key constraint in Germany, even for larger residential PV systems, was the available rooftop size. In light of the fact that a system with a nameplate capacity $15kW$ (90th percentile in 2010) covers an area of about $86m^2$ (~$926ft^2$) it does not seem surprising that installing a system beyond this size was only feasible for a very small fraction of residential PV investors. In recent years, the size of residential solar PV systems in Germany has fallen back to the level of 10 years earlier, which can be explained by a strong drop in FiT levels accompanied by a rise in retail electricity prices that have rendered sizing for self-consumption increasingly attractive.

While the analysis conducted in this article is not sufficient to establish causality of the effect of the different FiR schemes on PV sizing in both geographies, this section addresses the most obvious alternative explanation for smaller PV systems in California compared to Germany, namely the significantly higher solar irradiation (details provided in Table A.3). In particular, it may be argued that the higher yield from a given PV system may explain why Californian households have opted for smaller PV systems. However, as revealed in the latest residential energy consumption survey (EIA, 2009), the electricity consumption of an average single-family household in California is 50–70% higher than of its equivalent in Germany (BDEW, 2016). This is mostly due to the use of HVAC systems, which are more common in sunny California than in Germany. Hence, since the impact of higher solar irradiation on the size of PV systems is offset by the higher electricity consumption, it can be ruled out as an explanation for the significant differences between residential PV installations in the two focal geographies (average $PV/Load \sim 80\%$ in California as opposed to $\sim 150\%$ in Germany). In addition to the empirical analysis, a comprehensive simulation of the entire spectrum of input factors (cf. Figure A.6) reveals that our findings with regard to the impact of policies on the size of residential PV systems are sufficiently robust.

4 Conclusions and Policy Implications

Both our simulation results and the empirical data from California and Germany show how the design of feed-in remuneration (FiR) and its interplay with retail rates and system costs affect whether residential PV installations are economic as well as how they are sized (Couture and Cory, 2009; Seel et al., 2014). Since PV system sizes essentially determine a) the energy autonomy of residential households, b) the disruptive potential for electric utilities, and c) the impact on grid stability and requirements for infrastructure upgrades, our study points to three important implications for policy makers intending to manage residential solar PV as an active component of the electricity system.

1) Develop a vision for the role of residential solar PV and adjust policies accordingly

Our study reveals that policy makers have several levers at their disposal that affect the economics and sizing rationale of residential solar PV installations. Each of the prosumer paradigms brings individual challenges in terms of their integration into an emerging electricity system (Borenstein, 2015a; Ratnam et al., 2015). Policy makers and regulators should therefore pursue an explicit "prosumer strategy" and design their instruments according to the context-specific needs, rather than wait and see which prosumer paradigms evolve. Our analysis has shown that FiR design provides a sophisticated toolbox to adjust the rationale of residential PV investors on a very fine scale. The versatility of this instrument enables policy makers to navigate the significant trade-offs associated with residential solar, such as weighing economies of scale and accelerated decarbonization of households with "oversized" PV systems ($PV/Load > 1$) against their stronger grid impact and potential redistribution effects between customers. Given that many parameters that affect the economics of solar PV are constantly in flux and highly context specific, we invite policy advisors and researchers to employ the framework outlined in this paper to develop an understanding of the status quo and the near-term future of residential solar in a given geography. These capabilities for foresight will allow policy makers to make informed and timely decisions, which becomes increasingly important given the growing technological complexity in the emergent ecosystem around distributed solar, i.e. the domain of "distributed energy resources" (DER). For example, recalling the upper left area in Figure 3 ($p_{retail}/LCOE > 1 \wedge p_{FiR}/LCOE < 1$), the larger the spread between electricity rates and levelized PV costs, the more attractive an investment into devices for demand shift or energy storage becomes (Rodrigues et al., 2016a). Therefore, our framework can be used on the one hand as a map by various entities to identify potential areas of application for complementary DER technologies such as increasing PV self-consumption via energy storage (cf. Appendix Figure A.5c). And on the other hand, policy makers might use our framework to anticipate the drift towards unintended areas and intervene if deemed necessary (cf. NEM in California).

2) Ensure residential solar PV policies are comprehensible and credible

Studies have shown that customer education and sufficient competition between vendors are a prerequisite for driving down the soft costs of PV that may arise from customer acquisition, permitting, or installation. Therefore, a key priority for policy makers should be limiting the complexity of FiR designs since a comprehensible and credible scheme enables households to independently assess the economics of a PV system and actively approach, compare, and select the most attractive vendor. The German Feed-in Tariff of the mid 2000s is a well-documented example of how a coherent FiR design can enable the participation of a considerable number of households while spurring competition, technological learning through user-producer interaction, and quickly driving down soft costs (Hoppmann et al., 2014; Seel et al., 2014). To manage complexity, policy makers should try to minimize the number of instruments that simultaneously affect the economics of residential solar PV, and ensure consistency between these instruments. For example, while Germany's policy support for residential solar concentrated on the Feed-in Tariff scheme, homeowners in California faced a myriad of different federal, state, and local tax credits and rebates, regulated rate designs, and a FiR scheme that was coupled with the latter (Comello and Reichelstein, 2016b; Jeffries, 2016). As a result, even with a seemingly simple FiR design, it can be quite complex to assess solar PV economics due to customer-specific load profiles, electricity price levels, and location-specific LCOE. Policy makers should keep this in mind given the current debate around additional elements in rate design, such as demand, fixed, or standby charges (Proudlove et al., 2016). Rate components that do not reflect actual costs send unwanted price signals to customers, and may inhibit behind-the-meter distributed energy resources (DER) from leveraging their full potential in front of the meter.

Recognizing that the cost of solar, the retail price of electricity, and the compensation for electricity and capacity provided to the public grid are three separate things, policy makers should ensure that this distinction is reflected in their policy mix. For example, the current debate around NEM successor schemes across the United States in general, and in California in particular, appears clouded by the perception that FiR and electricity price levels are two sides of the same coin. By contrast, customers in Germany have long been used to the fact that the level of feed-in remuneration is decoupled from the going electricity rate, which is why nobody was surprised that the Feed-in Tariff gradually decreased when PV costs came down. In light of the increasing penetration of residential PV systems, this distinction is essential for a grounded debate around the value of solar.

3) Use FiR design to send appropriate price signals to residential PV owners

Considering the increasing maturity of solar PV technology, economists suggest a timely move towards integration of distributed solar, and other DER, into existing or emerging electricity market designs. Since this would pose significant revenue risks to residential PV owners – as well as creating a need for an entity that aggregates the behind-the-meter assets and coordinates their operation – we believe that a gradual introduction of actual price signals into existing feed-in remuneration schemes minimizes the cost of "[...] marketing one's electricity on the spot market", and thereby addresses the issue of excluding smaller actors, such as individual homeowners or community-based investors, from participating in the market (Couture and Gagnon, 2010, p. 956). Additionally, such amended or novel FiR designs could help reduce the costs that arise from an immediate policy switch, e.g. the likely increase of financing costs due to the shift in risk/return profiles of residential solar (Drabkin et al., 2015), or unintended effects, such as an escape into PV self-consumption associated with a massive load defection scenario.

Our study includes a number of limitations that can be regarded as avenues for further research. For example, we did not specifically elaborate on the effect of tiered rate designs (Darghouth et al., 2016a, 2011), the distinction between fixed vs volumetric charges (Hledik, 2014; Proudlove et al., 2016), or different ownership models and financing options (Comello and Reichelstein, 2016a). Future research could also study the effect of customer heterogeneity from a more holistic perspective, and could include an array of archetypical load profiles from customers in both geographies (Kwac et al., 2014; Tjaden et al., 2016). Last but not least, notwithstanding its importance for the debate around FiR design, we did not elaborate on the question of how the respective policy schemes are being funded (Huenteler, 2014; Pyrgou et al., 2016), and whether a cross-subsidization between different customer segments occurs, aspects that should undergo further scholarly investigation in line with the items outlined above.

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Appendix

Details on input data

PV supply data

PV supply ($P_{PVGen_{norm}}$) is based on irradiation data for the corresponding locations, assuming a fixed roof mount installation with a 20° tilt. Since our focal regions are in the Northern hemisphere, we assume a constant azimuth of 180° (southward orientation) and thus do not include any correction factors affecting the PV yield. Total losses in the conversion process from modules to the output gate of the inverter (AC) are assumed to be 14%.

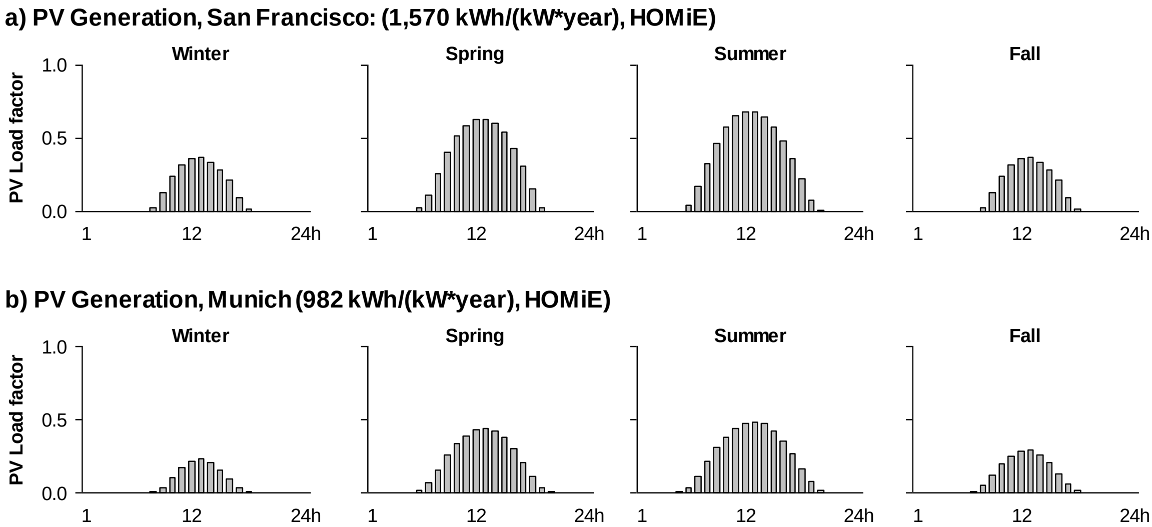


Figure A.1: Two seasonal PV generation profiles from HOMiE model: San Francisco (used as baseline for 3.1, and the analysis of California's NEM scheme in 3.2) and Munich (used as sensitivity in 3.1, and as baseline for analysis of Germany's FIT scheme in 3.2)

Given the local irradiation for San Francisco and Munich, the two exemplary geo-locations we selected in California and Germany, we arrive at an effective PV electricity yield of 1,570 $kWh/(kW \cdot a)$ and 982 $kWh/(kW \cdot a)$ respectively. These values are in line with the estimates 1,530 $kWh/(kW \cdot a)$ and 992 $kWh/(kW \cdot a)$ provided by NREL's PVWatts online platform (Dobos, 2014).

Table A.1: Technical input data for the simulation of residential PV in California and Germany

Parameter		California	Germany	Unit	Source
Location	-	San Francisco	Munich	-	Own
Daily horizontal irrad	$Irrad_j$	6.5723	3.1547	Wh/m²	TMY2
Actual cell efficiency	η_j	18.09%	18.09%	-	TMY2
Panel area	A	5.8824	5.8824	m²/kW_{peak}	Own
Tilt factor	θ	1.0579	1.0579	-	Own
System losses	τ_{system}	14.08%	14.08%	-	NREL
Inverter losses	$\tau_{inverter}$	4%	4%	-	NREL

Electricity demand data

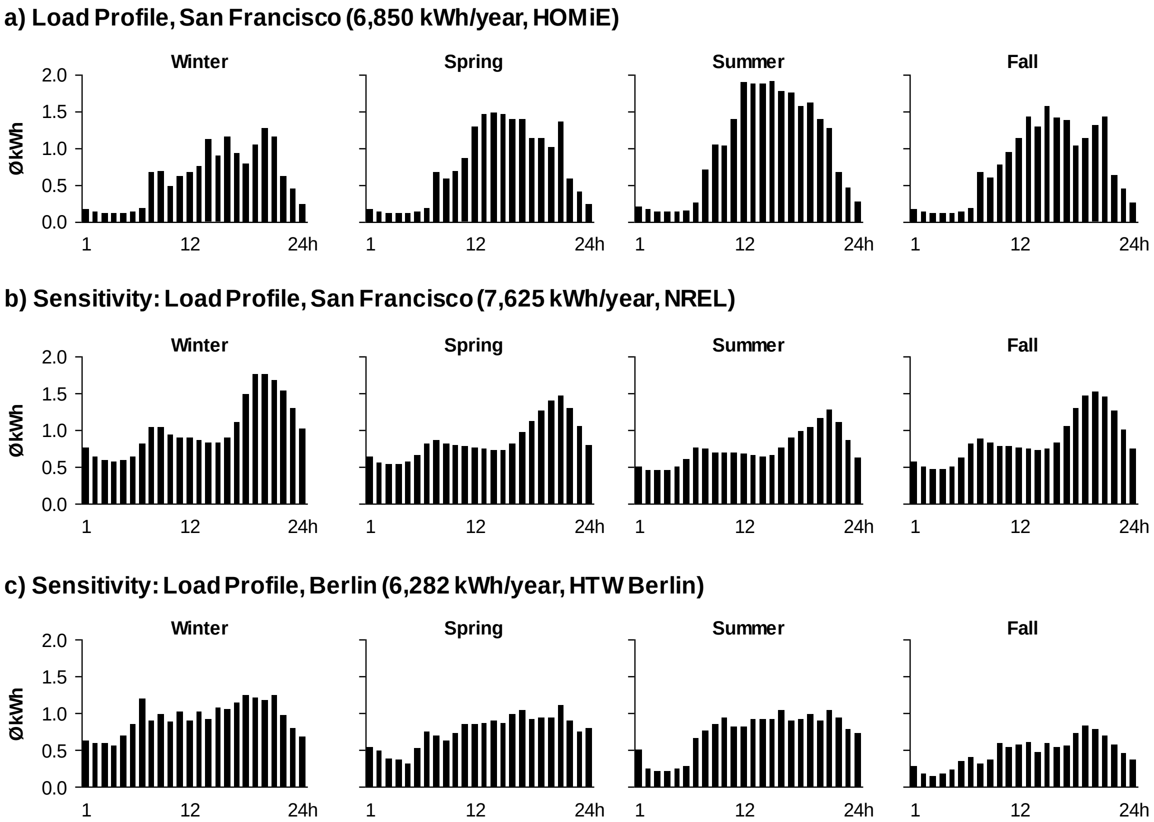


Figure A.2: Three seasonal electricity demand profiles corresponding to a 4-person single family households located; a) Location: San Francisco, modelled in HOMiE; b) Location: San Francisco, data provided by NREL; c) Location: Berlin ("Profile 17"), data provided by University of Applied Sciences Berlin (HTW)

Additional inputs and LCOE outputs used in the empirical policy analysis

Table A.2: Additional inputs and LCOE outputs used in the empirical policy analysis

	California			Germany		
Parameter	$LCOE_{net}$	$E_{threshold}$	$p_{FiR\,i\_L2} = NSCR$	$LCOE_{net}$	$k_{threshold}$	$p_{FiR\,i\_L2} = FiT_2$
Unit	ct/kWh	-	$/W	ct/kWh	kW	ct/kWh
2005	15.4	Residual grid consumption; depends on load profile E_{Load} and system size k ($SC > 50\%$)	0	41.0	30	57.58
2006	15.8		0	40.0	30	54.70
2007	16.2		0	35.0	10	51.97
2008	16.9		0	31.0	10	49.37
2009	14.1		0	29.0	10	45.41
2010	13.1		0	21.9	10	43.45
2011	12.7		3.73	18.3	10	31.90
2012	11.7		3.50	14.0	10	25.79
2013	10.9		4.27	9.7	10	17.92
2014	10.1		4.90	8.3	10	14.41
2015	9.6		4.13	8.0	10	13.56
2016	8.3		2.95	7.8	10	13.29
Source	Calculations based on inputs from Table 3; irradiation Fig. A.1 a)	NEM Program website (IOUs and CPUC)	NEM Program website (IOUs and CPUC)	Calculations based on inputs from Table 3; irradiation Fig. A.1 b)	FiT Program website (BNetzA)	FiT Program website (BNetzA)

Additional results

The interaction between feed-in remuneration levels and constraints

In order to showcase some of the conceptual differences in FiR design, Figure A.3 contrasts a generic NEM scheme with a generic FiT scheme. While both schemes are characterized by three different feed-in remuneration levels and an according number of constraints, they differ significantly. The NEM scheme is characterized by an initial FiR level that corresponds to the going retail rate, in this case a volatile, so called "time-of-use" rate (TOU) (cf. error bars attached to the FiR bar), that corresponds to a hypothetical three step function (off-peak, onpeak, super onpeak). The NEM design also includes an initial feed-in constraint that becomes binding as soon as the annual PV production exceeds the total annual load $E_{PVGen}(k) > E_{Load}$, i.e. once the feed-in remuneration over one year (provided in the form of bill credits) suffices to offset the residual electricity purchased from the grid. Beyond this "energy constraint", the remuneration level for excess electricity is reduced to the "Net Surplus Compensation Rate" (NSCR), which usually corresponds to the average spot market price (7am to 5pm) over the corresponding year in which the additional feed-in occurs. Beyond the eligibility period of both schemes ($i > T_{FiR}$), the compensation decreases to the going average spot market price, the level of which, in this case, is assumed to lie below today's value (cf. NSCR).

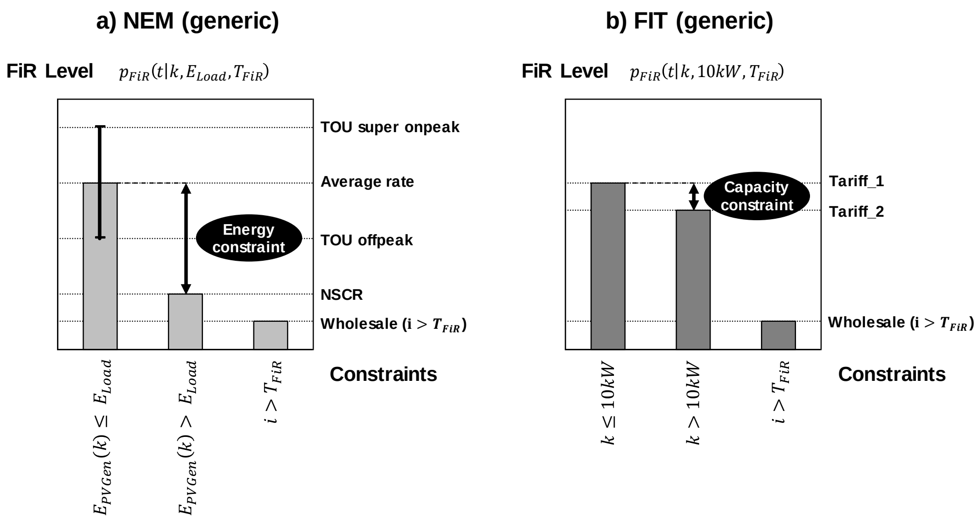
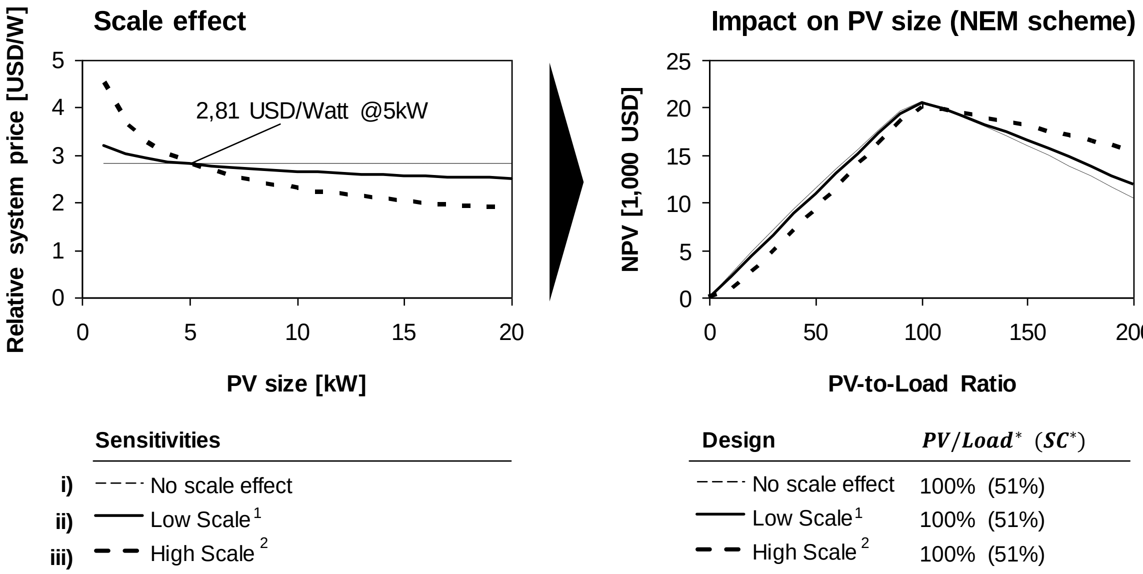


Figure A.3: The interaction of FiR levels and feed-in constraints; illustration based on two generic FiR designs, similar to a Net Metering and a Feed-in Tariff scheme

In contrast to the NEM design, the FiT scheme is characterized by a feed-in remuneration level that is set at the exogenous value "Tariff_1" for all solar PV installations with a nameplate peak generation capacity of below 10kW. Beyond this size, the single capacity constraint within the focal range of installation sizes (1–20kW) becomes binding, and the feed-in remuneration level for such systems is lowered to the exogenous value "Tariff_2".

The impact of scale effects

Since small-scale solar PV installations (residential, small commercial) are characterized by a large share of soft costs (Barbose and Darghouth, 2016), scale effects, recently estimated to lie around -0.19$/$W_{DC}$ in the US for a size increase from 5kW to 6kW (Gillingham et al., 2016), are an important means to achieving truly low-priced solar PV systems. Figure A.4 shows the impact of "low" and "high" scale effects for FiR scheme a-i) in Figure 2.



[1] Function: $SystemPrice_{rel} = 3.21 \cdot k^{-0.082}$, derived from (LBNL, 2016), (CSI currently interconnected, 2016)
[2] Function: $SystemPrice_{rel} = 4.54 \cdot k^{-0.297}$, derived from (Sonnen, 2016), (Solarchoice, 2016)

Figure A.4: The effect of economies of scale on optimal PV sizes; reference: FiR scheme a-i) (cf. Table 2)

Comparing PV/Load ratio between California and Germany

Table A.3: Comparing PV/Load ratio between California and Germany

	California	Germany	Unit	Source
Annual PV yield [1]	~1,500	~850	kWh/kW$_{peak}$	(Dobos, 2014)
Average annual load [2]	8,000	4,750	kWh	CA: (EIA, 2009) DE: (BDEW, 2016)
System size, PV/Load=100%	5.33	5.59	kW$_{peak}$	= row2/row1
System size, median emp. data	4.05	7.24	W$_{peak}$	Cf. Table A.3
Actual PV / Load ratio (estimate)	79%	150%	-	= row4*row1/row2

[1] Average of values taken from PV Watts for different locations in California (Redding, San Francisco, San Diego) and Germany (Hamburg, Cologne, Munich); [2] Values representative for four person, single-family household

Sensitivity analyses

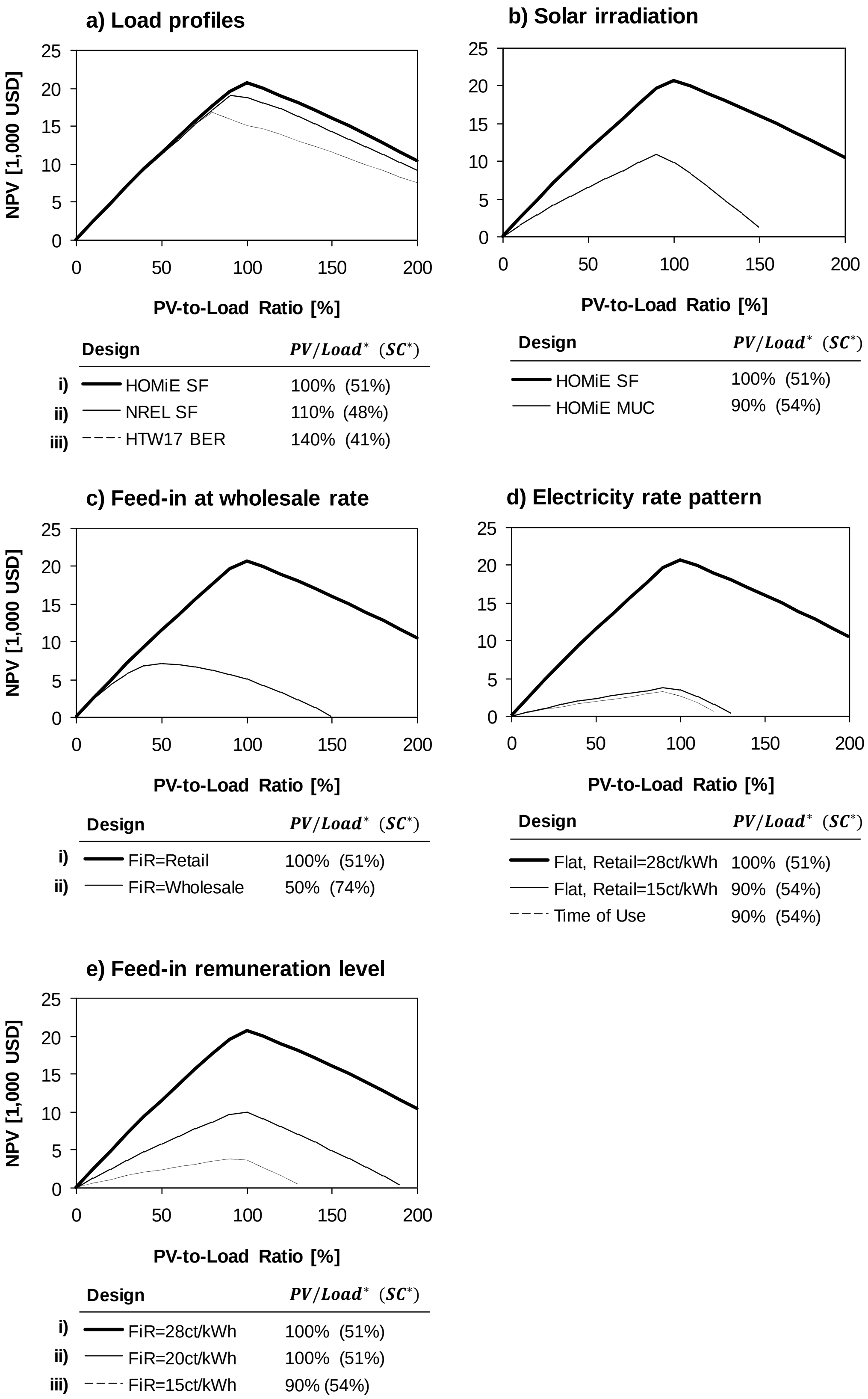


Figure A.5: Results of sensitivity analysis; reference: FiR scheme a-i) (cf. Table 2)

The combined effect of feed-in remuneration, rates, and LCOE on the sizing rationale of residential PV investors

To elaborate on the combined effect of feed-in remuneration, rates, and LCOE on the sizing rationale of residential PV investors, we elaborate on a series of $p_{retail_i}/LCOE$ and $p_{FiR_i}/LCOE$ ratios, each $\epsilon\ \{0.2; \ldots; 3.0\}$. To be able to freely set these ratios, we assume a simplified version of the FiT scheme outlined in Table 2, column b), with no growth in electricity rates ($p_{retail_{i+1}} = p_{retail_i}$), and no feed-in constraints ($no\ k_{threshold}$), and a lifetime that corresponds to the investment lifetime ($T_{FiR} = \mathrm{T} = 25a$)

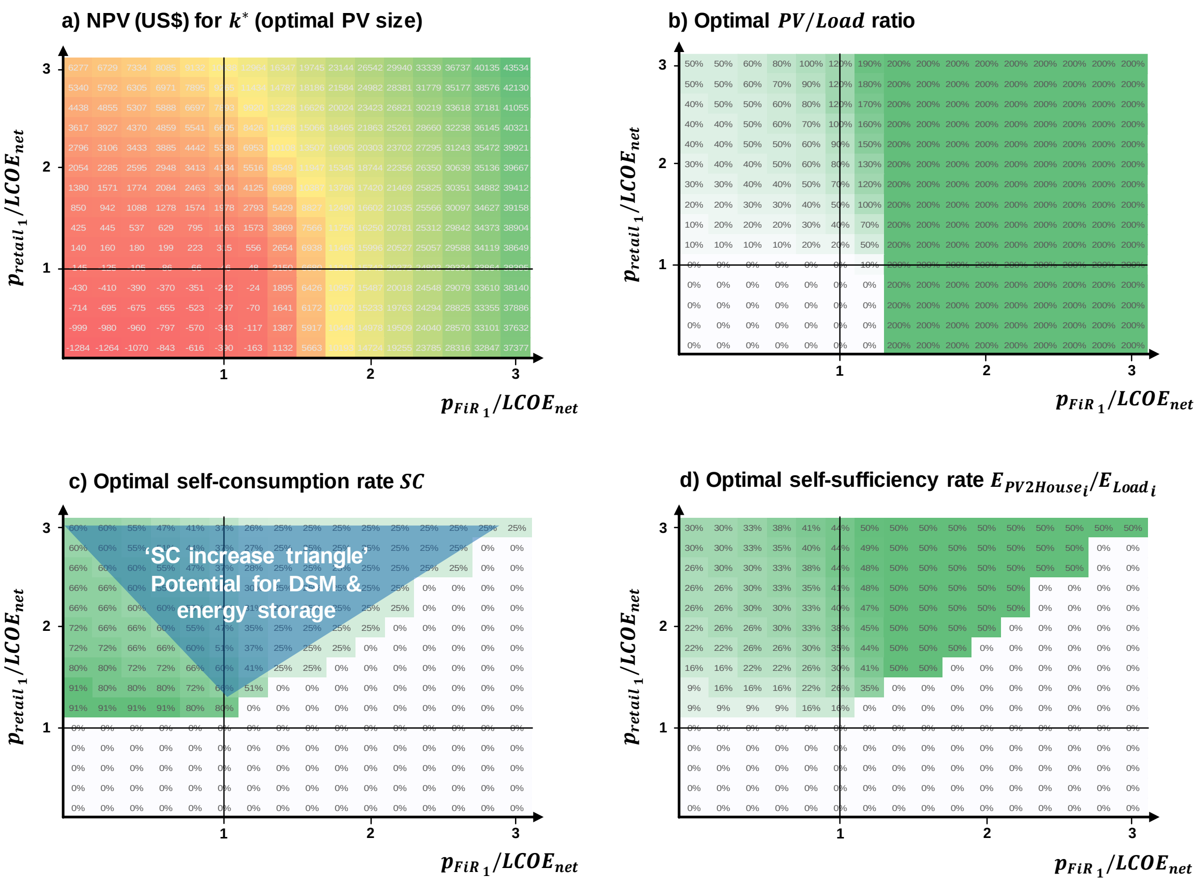


Figure A.6: The combined effect of feed-in remuneration, electricity prices, and LCOE on the sizing rationale of residential PV investors

Paper II

Revise and Resubmit to Organization Science until August 1, 2017

Hybrid Ambidexterity: How the Environment shapes Incumbents' Use of Structural and Contextual Approaches

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Abstract

According to the literature on ambidexterity, organizations can use structural or contextual approaches to simultaneously explore novel opportunities and exploit existing ones. So far, however, we know very little about what induces organizations to focus on structural vs. contextual ambidexterity, or how they combine the two approaches to maximize organizational learning. To shed more light on these questions, in this paper we investigate how the environment shapes a firm's use of structural and contextual ambidexterity. Drawing on a comparative, longitudinal case study of the four largest electric utility companies in Germany, we show that firms focused on structural ambidexterity whenever they perceived emerging opportunities in the environment as requiring organizational culture and capabilities fundamentally different from their own. Contextual ambidexterity, on the other hand, became particularly important when opportunities in the environment were both numerous and uncertain, requiring the organization to leverage the distributed attention and expertise of its frontline employees. We show that environments characterized by opportunities that are numerous/uncertain and require novel culture and capabilities lead organizations to invest in approaches that combine elements of structural and contextual ambidexterity, something we label *hybrid ambidexterity*. We identify two types of hybrid ambidexterity: split and joint. In addition, we provide the first evidence that a firm's ambidexterity approach is influenced by its exposure to environmental discontinuities, which is contingent on its geographic location and scope.

Keywords

Ambidextrous Organizations, Organizational Learning, Qualitative Research

1 Introduction

Organizational ambidexterity, i.e. a firm's ability to simultaneously pursue exploitation and exploration as two distinct modes of learning, helps protect incumbents against discontinuities in their environment (Andriopoulos and Lewis 2009; March and Simon 1958; Tushman and O'Reilly 1996). A quickly growing body of literature shows that organizational ambidexterity can be attained through structural or contextual approaches (Gibson and Birkinshaw 2004; Tushman and O'Reilly 1996). Structural ambidexterity entails assigning exploration and exploitation to separate business units, while senior management balances the two and develops a shared vision to avoid intra-organizational tensions (Burgers et al. 2009; O Reilly and Tushman 2004). With contextual ambidexterity, organizational members freely allocate their time between the two modes of learning, with no structural separation. This approach requires a supportive organizational context—which can be attained, for example, by cultivating a culture that reconciles seemingly contradictory elements, such as discipline, stretch, support, and trust (Gibson and Birkinshaw 2004).

The extant literature provides detailed insights into structural and contextual ambidexterity individually. However, we currently lack integrated studies of (a) what induces organizations to focus on one mode vs. the other, and (b) when and how they combine the two (Kauppila 2010). Understanding the antecedents of structural vs. contextual ambidexterity and their combination in organizational settings is critical for providing targeted recommendations to managers on when to use each mode and how best to leverage synergies between them. In fact, previous research suggests that the relative focus on the two modes of ambidexterity may depend on firms' environment (O'Reilly and Tushman 2013). Moreover, scholars propose that rather than being alternatives, structural and contextual ambidexterity may be complementary with regard to their advantages and shortcomings, such that organizations often use both in combination (Raisch and Birkinshaw 2008). So far, however, evidence on the relationship between the two approaches remains largely anecdotal and inconsistent; the few empirical studies provide little detail on antecedents or how firms combine their elements (Chang and Hughes 2012; Raisch and Birkinshaw 2008; Simsek 2009).

In this paper, we focus on the role that firms' environment plays in their ambidexterity approach and investigate *how the environment shapes a firm's use of structural and contextual ambidexterity.* To this end, we conducted a comparative, longitudinal case study among the four largest incumbent electric utility companies in Germany. This setting is well suited for our purpose because (a) in recent years the sector has undergone two major environmental discontinuities—the emergence of renewable energy and "new downstream"—that required incumbents to engage in ambidexterity, and (b) firms differed in their ambidexterity approaches. Contrasting the detailed initiatives firms engaged in—both across time and across organizations—allows us to draw important conclusions about how the use of structural and contextual elements is related to environmental characteristics. Moreover, we explore how firm characteristics affect firms' responses to environmental stimuli.

Our study makes three contributions to the literature on ambidexterity. First, we show how a firm's use of structural and contextual elements of ambidexterity is strongly affected by its environment. When the environmental discontinuity required fundamentally new culture and capabilities, but involved a clearly delimited set of potential new opportunities, firms drew mainly on structural elements when trying to become ambidextrous. This was done to avoid cultural clashes and quickly build new capabilities top-down. When the discontinuity involved a vast array of uncertain potential new opportunities, firms complemented structural elements with contextual elements, using the distributed attention and expertise of their frontline employees to enhance opportunity search. Second, we show in detail how firms combine structural and contextual elements in their quest for ambidexterity. While literature has primarily studied structural and contextual ambidexterity in isolation, we demonstrate that firms use both approaches in parallel, something we call *hybrid ambidexterity*. We show that firms pursue two types of hybrid ambidexterity: (a) they pursue structural and contextual ambidexterity within the organization in parallel, but in an isolated way (*split hybrid ambidexterity*); (b) they use new organizational forms that combine structural and contextual elements, e.g. in the form of permeable venturing units (*joint hybrid ambidexterity*). Third, we also provide preliminary evidence for how firm approaches to ambidexterity are influenced by firm-level factors. Whereas the environment induced specific firm responses in all the companies we studied, we find some differences in the timing and design of ambidexterity approaches across firms. We show that these differences can be explained primarily by firms' exposure to environmental discontinuities resulting from differences in geographic location and scope.

2 Theoretical Background

Although the tension between flexibility and efficiency has long been recognized in the literature on organizational theory, March (1991) was one of the first to identify exploration and exploitation as two distinct modes of learning. Exploration comprises searching for and experimenting with options far from the existing knowledge base to enhance organizational flexibility. Exploitation, on the other hand, involves building upon and refining existing knowledge to foster efficiency (March 1991). Although these modes compete for resources, March noted that organizations had to pursue both forms to be competitive in the short run, while ensuring long-term survival in times of environmental discontinuities.

Following March's article, a long stream of literature has investigated how firms can manage the trade-off between exploration and exploitation (Lavie et al. 2010). While some scholars suggested temporal cycling between the two modes (e.g., Nickerson and Zenger 2002; Siggelkow and Levinthal 2003) or inter-organizational balancing, e.g. through joint ventures, alliances, or acquisitions (e.g., Lavie and Rosenkopf 2006; Stettner and Lavie 2013), a third stream has investigated how organizations can organize internally to accommodate both types of learning simultaneously. Here, the concept of *ambidexterity* was coined to describe a firm's capacity to simultaneously explore and exploit (Duncan 1976; Tushman and O'Reilly 1996).[1] A plethora of studies shows a positive relationship between ambidexterity and firm performance (see Junni et al. 2013, for a review), innovation (e.g., Burgers et al. 2009; Tushman et al. 2010), and survival (e.g., Mitchell and Singh 1993), particularly in times of environmental discontinuities.

2.1 Two types of ambidexterity: structural and contextual

The literature distinguishes two ideal types of ambidexterity: structural and contextual (Raisch and Birkinshaw 2008). These two types differ with regard to three core criteria: (a) the degree of structural separation between exploration and exploitation activities; (b) the degree of employees' specialization on exploration or exploitation; and (c) the role of managers in facilitating ambidexterity (see Table 1).

[1] Some authors subsume temporal cycling and inter-organizational balancing through joint ventures, alliances, or acquisitions under the concept of ambidexterity. In our study, we follow the narrower definition of ambidexterity proposed by Lavie et al. (2010), which describes firms' capacity to *simultaneously* (rather than sequentially) engage in exploration and exploitation *within the same organization*. Accordingly, in the following, we focus on structural and contextual ambidexterity as the two major ways described in the literature that allow firms to achieve this end.

Table 1: Characteristics of structural and contextual ambidexterity

Criterion	Structural Ambidexterity	Contextual Ambidexterity
Degree of structural separation between exploration and exploitation	Exploration and exploitation structurally separated	Exploration and exploitation not structurally separated
Degree of specialization of frontline employees in exploration and exploitation	Frontline employees in units strongly specialized in either exploration or exploitation	Frontline employees switch between exploration and exploitation
Role of senior managers in facilitating ambidexterity approach	Senior managers integrate and balance between exploration and exploitation units	Senior managers provide context that facilitates cycling of frontline employees between exploration and exploitation

Structural ambidexterity

The literature on structural ambidexterity suggests that in order to deal with the inherent tension between exploration and exploitation, organizations should structurally separate them by forming separate units (O'Reilly and Tushman 2013; O Reilly and Tushman 2004; Tushman and Rosenkopf 1996). This allows them to create units with competencies, incentives, processes, and cultures that are internally aligned and specifically tailored to the need to explore or exploit (Gilbert 2006; O'Reilly and Tushman 2008; Tushman and O'Reilly 1996). According to Denison (1990, p.2), organizational culture comprises "the underlying values, beliefs, and principles that serve as a foundation for an organization's management system as well as the set of management practices and behaviors that exemplify and reinforce those basic principles." Whereas exploitation units usually follow a mechanistic design, with centralized decision-making, tight cultures, and a focus on efficiency and control (Benner and Tushman 2003), exploration units tend to be more organic, with more decentralized decision-making, entrepreneurial cultures, and a focus on flexibility (Boumgarden et al. 2012; Lavie et al. 2010).

In structural ambidexterity, frontline employees in each unit are strongly specialized in activities related to exploration or exploitation. This specialization safeguards the activities of the exploration units from potentially harmful cultural and procedural spillovers from the mainstream business (Benner and Tushman 2003; Gilbert 2006). Similarly, exploitative units can focus on improving existing products and serving existing customers without being distracted by the need to consider future alternatives (Simsek 2009).

To hold the different units together, the literature stresses the importance of a "common strategic intent, an overarching set of values, and targeted structural linking mechanisms to leverage shared assets" (O'Reilly and Tushman 2008, p.193). Developing these integration mechanisms and managing the tensions between exploration and exploitation units is the task of senior management (Burgers et al. 2009; Jansen et al. 2009a; Lubatkin et al. 2006). Senior managers need to recognize the contradictions inherent in exploration and exploitation, and devise strategic measures that reconcile the tensions at the organizational level—e.g., by managing budget allocation to potentially conflicting activities (Andriopoulos and Lewis 2009; Burgelman and Grove 2007; Smith and Tushman 2005).

Contextual ambidexterity

An alternative perspective on how firms can achieve ambidexterity is offered by the literature on contextual ambidexterity. According to this approach, organizations should not structurally separate exploration and exploitation activities, but instead create a context that allows employees to simultaneously explore and exploit within the same unit (Birkinshaw and Gibson 2004; Birkinshaw and Gupta 2013; Gibson and Birkinshaw 2004). Rather than specializing in either exploration or exploitation, employees decide themselves how to divide their time between exploration and exploitation (Gibson and Birkinshaw 2004; Raisch and Birkinshaw 2008; Simsek 2009). As an example, Adler et al. (1999) describe how employees at Toyota working on routine tasks such as automobile assembly (exploitation) continuously improve processes, change jobs, and experiment with alternative solutions to enhance the cost, performance, and quality of products (exploration). This contextual switching allows business units to flexibly respond to changes in demands without having to coordinate the tensions between disparate units. At the same time, however, the need to balance exploration and exploitation puts a strain on the frontline employees, who must deal with conflicting tasks and demands (Andriopoulos and Lewis 2009; Gibson and Birkinshaw 2004; Patel et al. 2013).

Since, in contrast to the structural approach, the decision on how much to explore or exploit lies with individual employees, management is not directly involved in integrating or balancing exploration and exploitation initiatives. Rather, the key task of management lies in providing a context that facilitates and incentivizes employees' flexible switching between exploration and exploitation. According to Ghoshal and Bartlett (1994), the context comprises the "systems, processes, and beliefs that shape individual-level behaviors in an organization." In other words, managers must devise an organizational design (including structures, practices, culture, and climate) that promotes both efficiency and flexibility (Cordery et al. 1993; Patel et al. 2013; Simsek 2009). Previous work suggests that this includes creating an organizational culture that reconciles seemingly contradictory elements such as discipline, stretch, support, and trust (Andriopoulos and Lewis 2009; Gibson and Birkinshaw 2004; Patel et al. 2013).

2.2 The relation between structural and contextual ambidexterity

While a plethora of empirical studies have looked at structural and contextual ambidexterity *individually*, we currently lack *integrated* studies that span both types. In particular, we currently know very little about (a) when firms might focus on one approach or the other, and (b) how firms might combine the two approaches to leverage their respective strengths.

When do firms focus on structural vs. contextual ambidexterity?

Building on the studies by March (1991) and Tushman and O'Reilly (1996), much work has gone into identifying the antecedents of ambidexterity as a whole (e.g., Jansen et al. 2012; Jansen et al. 2009a; Jansen et al. 2006; Mom et al. 2007). In this context, for example, it has been found that ambidexterity may be particularly important in times of high environmental dynamism (Jansen et al. 2006; Junni et al. 2013; O'Reilly and Tushman 2008) and environmental uncertainty (Jansen et al. 2009b; Sidhu et al. 2007). Moreover, scholars have identified firm-level antecedents that contribute to ambidexterity, such as firm size and resources (Cao et al. 2009; Sidhu et al. 2004), firm financial performance (Holmqvist 2004; O'Reilly and Tushman 2008), and the experience and cognition of the senior management team (Mom et al. 2015; Raisch et al. 2009; Smith and Tushman 2005).

So far, however, few systematic studies have asked why a firm might focus on structural vs. contextual ambidexterity (Lavie et al. 2010). Initial studies suggest that contextual ambidexterity might be better suited for small to medium-sized firms, which lack the resources for separate exploration and exploitation units (Duncan 1976; Lubatkin et al. 2006; Raisch et al. 2009). Moreover, it has been proposed that the relative focus on structural vs. contextual ambidexterity depends on a technology's stage in the innovation life-cycle (Raisch and Birkinshaw 2008). Jansen et al. (2013), for example, found that incumbents often created new businesses through structural ambidexterity, and switched to contextual once the technology had become more accepted in the firm. Conversely, in a case study of Hewlett-Packard, House and Price (2009) show that the laser printing business resulted from exploration within established units (contextual ambidexterity), followed by the establishment of a separate business unit (structural ambidexterity).

Amid these conflicting findings, O'Reilly and Tushman (2013, p. 330) suggest that a firm's focus on structural vs. contextual ambidexterity may not only depend on the innovation life-cycle, but that "the different ways of achieving ambidexterity may be more or less useful contingent on the nature of the market faced." If the effectiveness of the two approaches actually depends on the organizational environment, this has important implications for corporate managers wishing to implement ambidexterity. In this case, studying the relationship between the environment and ambidexterity would allow us to derive targeted recommendations for managers on when to focus on which approach. Moreover, insights into the usefulness of ambidexterity approaches in different environments could help us refine our understanding of the link between ambidexterity and organizational performance.

How do firms combine structural and contextual ambidexterity?

Besides providing limited insights into the antecedents of structural vs. contextual ambidexterity, the literature also has relatively little to say about how firms combine the two approaches in practice. In recent years, a growing number of scholars have pointed to the complementary nature of structural and contextual approaches to ambidexterity (Hill and Birkinshaw 2014; O'Reilly and Tushman 2013; Simsek 2009). In their review of the literature, Raisch and Birkinshaw (2008), for example, state that "at first sight, organizational ambidexterity's antecedents, which include structural, contextual, and leadership-based factors, have been implicitly conceptualized as alternative solutions. [...] An in-depth analysis of these studies, however, reveals complementarities between the different paths to ambidexterity." Referring to Lawrence and Lorsch's (1967) seminal work, they argue that approaches building on differentiation, such as the structural approach, need to be complimented by integrative approaches for organizations to deliver effective outcomes.

Following this line of argument, scholars have suggested that rather than using only one type of ambidexterity, in reality firms can be expected to use a combination of structural and contextual approaches (Kauppila 2010; Raisch and Birkinshaw 2008). This argument is backed up by the classical literature on organizational change, which suggests that successful organizational change often results from a combination of induced, top-down strategic processes (including setting up separate exploration units as part of structural ambidexterity) and autonomous, bottom-up developments (resulting from employee initiatives in contextual ambidexterity) (e.g., Weick and Quinn 1999).

Despite accumulating anecdotal evidence that firms may be using both structural and contextual approaches, we currently lack insights into how different elements of both might be combined in change initiatives (Chang and Hughes 2012; Raisch and Birkinshaw 2008; Simsek 2009). By combining ambidexterity approaches to leverage their respective strengths, organizations may be able to improve both their performance and their chances of long-term survival. Therefore, deeper insights into when and how organizations blend structural and contextual ambidexterity could yield important implications for managers.

3 Method

To investigate *how the environment shapes a firm's use of structural and contextual ambidexterity* we use qualitative case study research. Case study research is well suited for deriving rich descriptions of empirical phenomena for which little theory exists (Eisenhardt 1989; Siggelkow 2007). Since existing literature has not yet fully explored and conceptually modeled environmental influence on organizational ambidexterity, we use qualitative research to explore the mechanisms at work (Yin 2009).

3.1 Research setting

We conducted an in-depth, longitudinal, comparative case study of the four largest German electric utility companies—E.ON, RWE, EnBW, and Vattenfall—in the period 2005–16 (Eisenhardt and Graebner 2007). From a theoretical sampling perspective, this setup is ideal for shedding light on our research question, since (a) the German electricity sector faced two major environmental discontinuities in this time frame that required incumbent firms to engage in ambidexterity, and (b) firms differed in their ambidexterity approaches. Moreover, Germany is widely regarded as a frontrunner in transitioning to environmentally friendly energy technologies. Therefore, studying the German case can provide important insights for managers and policy makers in other countries that have started similar transitions, e.g., the U.S.

Until the early 2000s, the German electricity sector was organized into regional monopolies, which allowed incumbents to reap above-normal returns and focus on exploitation. Starting in 2005, the sector faced two major discontinuities in the regulatory, competitive, and technological environment that radically challenged incumbents' ways of doing business. In the first phase, the sector saw the rise of renewable energy as a technological alternative to conventional power generation[2] (Hoppmann et al. 2014). In the second phase, starting around 2009, the electricity sector faced a sharp decline in profit margins on upstream power generation, which forced utilities to search for new business models and technologies in the downstream part of the electricity value chain (so-called "new downstream").

While both trends affected the entire German electricity sector, we concentrate on studying the ambidexterity activities of the four largest utilities (the "Big Four"). We do so since these firms represent classical incumbents that faced a strong incentive to enhance their level of exploration and pursue ambidexterity approaches in response to the aforementioned discontinuities. All four possessed sufficient resources to engage in the costly adaptation processes necessary to achieve organizational

[2] Between 2000 and 2014 the share of electricity generated from onshore wind turbines or solar PV modules rose from 1.6% to 14.6%. The installed generation capacity from these sources grew from about 6.2 gigawatts to about 76.3 gigawatts, i.e. it increased from less than 5% to more than 38% of the total power plant fleet in Germany.

ambidexterity, which clearly distinguishes them from their smaller competitors[3]. At the same time, however, a closer look at the firms' activities revealed that each firm in our sample chose ambidexterity approaches that differed in their emphasis on the structural and contextual elements discussed in the literature. Contrasting firm responses across time allowed us to draw important conclusions about how the use of structural and contextual elements is related to environmental characteristics. Studying differences across firms at each point in time allowed us to gain insights into how firm responses to environmental stimuli depend on firm characteristics.

3.2 Data collection and analysis

To arrive at a thorough understanding of firms' ambidexterity approaches and environmental antecedents over time, we drew on a wide array of data sources, namely (1) archival data, (2) interviews with industry experts, and (3) personal interviews with representatives of the four utilities (Boumgarden et al. 2012).

First, we used archival data to develop a granular event timeline for the utility sector and a holistic overview of each firm's history, strategy, and scope of activities. For this purpose, we collected several thousand company-external documents such as annual reports, letters to shareholders, corporate brochures and profiles, employee presentations, corporate news releases, corporate webpages, videos of top managers' talks, and presentations. Moreover, we used the DowJones Factiva[4] database to gather an extensive body of press articles (journals, magazines, newspapers, news wires). Based on this large empirical dataset we developed comprehensive archival data dossiers for each firm in our sample. These dossiers comprised information on the initiatives that firms launched in response to renewable energy and downstream opportunities, as well as the demographic background of selected senior executives involved.

Second, we used semi-structured interviews with industry experts to validate our findings on environmental changes and gain further insights into the approaches chosen by our sample firms as well as the rationales behind them. Industry experts included strategy consultants; technology providers; representatives from other utilities and industry associations; and well-informed trade journalists. Besides conducting 14 formal telephone interviews, we discussed our emergent findings in a series of informal interviews with industry experts and utility representatives during the 2015 annual meeting of VGB Powertech[5], the leading technical association of utilities in Europe. The expert

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[3] This assumption was confirmed in a pre-study interview with the CEO of a German municipal utility, who told us that the responses of smaller utilities to environmental change were often lagging behind, since they could not afford larger investments in novel technologies or business models.

[4] To narrow down the search scope we developed a string of keywords that contained the name of the firm in combination with the most important power-generation technologies.

[5] The members comprise 480 European power and heat generators, which operate and maintain a global generation fleet totaling 458 gigawatts.

interviews confirmed that the company approaches differed considerably over time. Based on the interviews, we developed a preliminary theoretical framework. In particular, we established initial links between the ambidexterity approaches used by our sample firms and the organizational environment.

Finally, we used 30 interviews with current and former representatives of the four sample firms to shed light on the firms' ambidexterity initiatives in terms of their design and antecedents. Previous research suggests that ambidexterity is a multi-level phenomenon that may involve a wide variety of actors and processes. Thoroughly understanding ambidexterity in our focal firms therefore required us to collect data on multiple levels (from individuals to entire business units) and on employees in different positions in the organizational hierarchy (both frontline staff and top managers) (Birkinshaw and Gupta 2013).

To explore individual firm initiatives, we approached current and former organizational members at different hierarchical levels who we knew were (or had been) involved in the company's renewable-energy or new-downstream activities. In addition, we made use of snowball sampling, asking each interviewee whether there were important members of their organization with whom we should discuss our research. Interviews lasted between 30 and 90 minutes (60 minutes on average) and were audio-recorded and subsequently transcribed. As part of the interviews, we asked interviewees to describe specific initiatives their organizations used to deal with the two challenges of renewable energy and new downstream (setting up new business units, projects, or change efforts). We decided to capture a firm's ambidexterity effort at the level of individual initiatives, since (a) this allowed us to draw a complete picture of the diverse ways through which firms tried to achieve ambidexterity; and (b) by discussing concrete initiatives with our informants, we could obtain very detailed information about their setup and underlying rationale.

For each initiative, we then drew on the three categories described in Table 1 to inquire whether it possessed characteristics of the contextual or structural ambidexterity approach. Since the literature provided sufficient guidance on how to differentiate the two ambidexterity approaches, for this step we directly drew on concepts described in the literature. Moreover, we explicitly asked our informants why the initiatives had been set up as they had; how initiatives for renewable energy compared to those for new downstream; and how their firm's initiatives differed from those of the other "Big Four". Since the antecedents of ambidexterity approaches were not well described in the literature, we used a more inductive approach here, asking open questions and experimenting with alternative constructs. To ensure the validity of our findings, we triangulated between the interviews as well as the archival data.

Going back and forth between data collection and theory development, we then iteratively refined our preliminary theoretical framework until theoretical saturation was reached (Miles and Huberman 1984). In this context, to fully capture the richness of the constructs, we developed a coding scheme according to the guidelines of Flick (2009), which we implemented in the qualitative data analysis software MaxQDA. In particular, for each of the firms, we created a list of all initiatives for both renewable energy and new downstream and coded our interview transcripts according to whether the initiatives exhibited features of structural and/or contextual ambidexterity. Similarly, we scanned our transcripts for statements that described the characteristics of the two environmental discontinuities or links between environmental characteristics and the firms' initiatives, as well as company characteristics that could explain differences across firms. Using pattern matching, we then established the relationships between the nature of environmental change, firm characteristics, and the design of the firms' ambidexterity initiatives. Table 2 provides an overview of the data sources used in the study.

Table 2: Overview of firm sample and data sources

Category		Firm				Sum
		RWE	E.ON	EnBW	Vattenfall	
Firm interviewees[a]	Power Generation (conventional, renewable)	3/2	2/2	3/2	1/1	9
	New Downstream (R&D, NPD, In-house, Sales)	6/5	3/1	2/1	3/2	14
	General Management/Strategy	2/2	1/1	1/1	1/1	5
	Other	1/0	1/0			2
	Sum	12	7	6	5	30
Expert interviewees[a]	Consulting	X	X	X	X	8
	Utility	X	X	X	X	2
	Technology Provider	X	X	X	X	1
	Advocacy	X	X			1
	Banking	X	X	X		2
	Sum					14
Archival data	Annual Reports	1974-*	1999-*	1998-*	2002-*	87
	Press Data (Factiva)	4,123	3,134	1,826	3,438	12,566
	Press Data (Desk Research)	78	89	26	22	215

[a] Numbers indicate "Persons in function interviewed/number who were members of the executive board"

Once we felt that the theoretical framework was robust, we re-interviewed four company representatives to present our findings and framework and ask them to critically consider whether our results concurred with their observations and experience. The interviewees responded that, from their perspective, our framework summarized their perspective in a very useful way, and made only minor suggestions for improvements, which we subsequently implemented.

4 Findings

The starting point: monopolies, profits, and exploitation

Until 1998, the German electric utility market was organized into regional monopolies, which granted electric utilities exclusive rights to generate, transmit, and sell electricity. In this stable environment, firms had a mandate to ensure the security of supply, and concentrated their generation business on large-scale power plants that used hard coal, lignite, or nuclear fuel. When the monopolies were dissolved as part of market liberalization in 1998, the utility industry was restructured through a series of mergers and acquisitions. This led to the rise of the four large utility firms—RWE, E.ON, EnBW, and Vattenfall Germany, later dubbed the "Big Four"—that provided electricity to more than 40M customers and had a market share of 54% by 2003. In later years, the Big Four leveraged their dominant position in the German electricity system and exploited their written-down power generation fleet. As the manager of a local utility stressed, "[n]uclear power plants, black coal power plants, gas power plants—all plants were money-printing machines back then" (E8[6]). In the words of one E.ON manager, this led to a situation where "there were essentially no limits for the electric utilities. [...] The share prices frequently reached new highs, profits went up every year, there was no way you could have prevented this from happening" (U4). Consequently, technological activities mostly focused on maintaining and incrementally improving existing plants that had been put into operation in the 1960s and 1970s. "You had a business model that had worked for 40, 50 years. No one thought this would change any time soon" (E10).

4.1 The first challenge: going green

The situation changed considerably with the increasing diffusion of renewable-power technologies in Germany. Since the 1970s, social movements had been urging the German government to phase out nuclear power and incentivize renewables. That pressure finally bore fruit in the first public demonstration projects for wind and solar power in the 1990s; the political decision to exit nuclear power in 1998; and the inauguration of the Renewable Energy Source Act in the year 2000. This last policy measure granted investors in renewable energy plants the right to sell their electricity well above the market rate. This in turn, led to a surge in annual installations of solar, wind, and biomass power plants by new market entrants, which triggered technological learning and cost reductions in renewable technologies.

Of course, the rise of renewables did not go unnoticed by the Big Four, but they were initially very hesitant to embrace them. Renewables were "not taken seriously" (E3), were considered "insanely expensive, a case of excessive subsidization" (U9), and "inefficient" (U15). Managers were convinced

[6] We use the codes E1–E16 and U1–U30 to reference industry experts and utility representatives respectively.

that "electricity could not be generated safely and cheaply using renewables" (E3) and that "policymakers will eventually come to their senses" (E3). Accordingly, the firms first tried to "block the market entry of renewables and protect the conventional generation business" (U4) through lobbying. Apart from minor activities in local niche markets, the Big Four therefore made no notable investments in renewables, such that by 2007 their share in the German renewable market was still less than 8% (see Figure 1). As one manager stressed, the utilities were "practically inactive in the renewable business" (E10) and "there were a few people who were doing things in renewables, but when it came to strategic investments, renewables were—simply speaking—the enemy. One did not want to 'create competition for oneself'" (E10). Only in 2007, when the Big Four began losing market share, did managers see that they had to invest or risk being left behind. As one manager recalls, "We realized that [...] the share of conventional energy would shrink and that growth would primarily take place in renewables. [...] And of course, you don't want to lose market share, so we said that we must enter the renewable technologies" (U4).

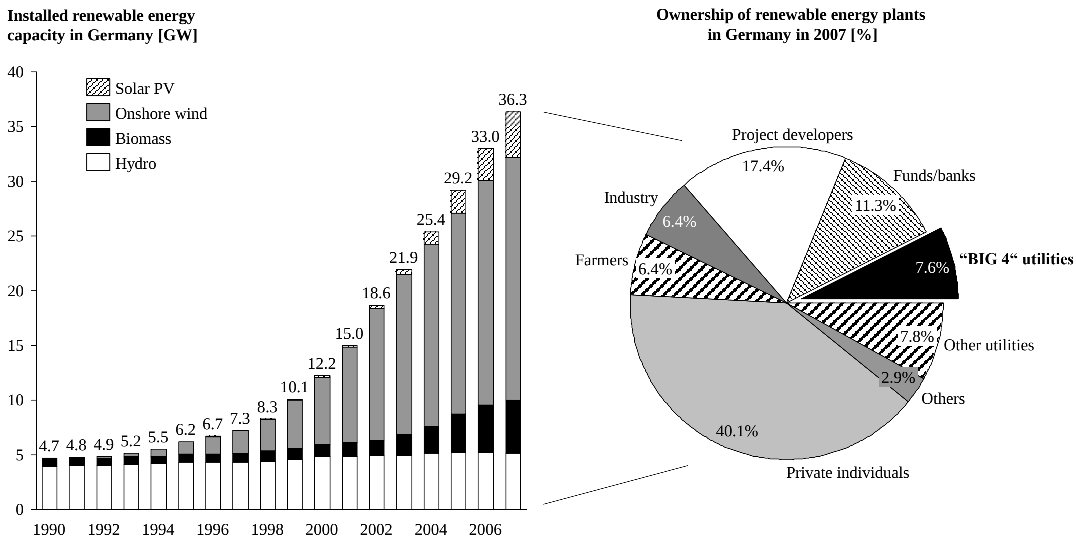

Figure 1: Development of renewable energy capacity in Germany and market share of the "Big Four" utilities in 2007

The approach: structural ambidexterity

Entering renewables required the utilities to develop new processes to engineer, build, run, and maintain renewable plants. One option would have been to assign these activities to existing business units, which well understood how to carry them out for conventional plants. Yet, our analysis shows that all the Big Four opted to create dedicated business units for renewables, clearly separated from the rest of the organization. RWE created the unit "Innogy," E.ON "Climate and Renewables," EnBW "Renewables," and Vattenfall "Vattenfall Wind."

The new units were often staffed with external hires with previous experience in renewables, tasked with working on renewables full-time. As a consultant explained, "Everything that has to do with renewable generation can be found in these units; the old generation units don't deal with renewable energy" (E3). Only at EnBW was the unit more closely integrated, such that plant maintenance was done by employees who switched between working on conventional and renewable technologies. In all cases, top managers' job was to allocate budgets between the new and old units. Moreover, the top managers were heavily involved in selecting the technologies to be pursued in the new units. Table 3 categorizes the utilities' initiatives into structural and contextual ambidexterity approaches according to the criteria presented in Table 1. It shows that to address the challenge of renewable energy, all utilities closely followed the structural approach, with the exception of EnBW. Table A.1 in the appendix provides more details and exemplary quotes.

Table 3: Firm initiatives to address the challenge of renewable energy technologies

				Structural ambidexterity			Contextual ambidexterity		
Firm	Initiative	Launch	Activity	Ex/ex separated	Employees specialize	TMT integrate	Ex/ex not separated	Employees switch	TMT set context
RWE	Innogy	2008	Engineering, procurement, construction, and operation of renewable energy technologies	X	X	X			
E.ON	Climate & Renewables	2007	Engineering, procurement, construction, and operation of renewable energy technologies	X	X	X			
EnBW	Renewables	2008	Engineering, procurement, construction, and operation of renewable energy technologies	X	X	X		X	
Vattenfall	Wind	2008	Engineering, procurement, construction, and operation of renewable energy technologies	X	X	X			

The rationale: dealing with opportunities requiring different culture and capabilities

So why did the Big Four go structural when entering renewables? Our findings suggest that the approach was chosen for three main reasons (see Table 4). First, separation was deemed necessary because the great distance between environmental opportunities and the organizations' culture implied a lack of support for renewables in the existing units. Due to longstanding experience with fossil-fuel technologies, the culture in the conventional business strongly favored large-scale nuclear, coal, and gas power plants. Over the years, engineers in the companies had come to see reliability, technological efficiency, and cost-effectiveness as the most important criteria for judging the merits of energy-generation technologies. Since these values had become deeply engrained into the companies' culture, renewables were regarded as technologies that were immature, inefficient, and strongly dependent on public subsidies. As one manager reported, engineers in the conventional units "saw renewables as a threat: 'What's all this nonsense? It's too expensive anyway!'" (U9). Therefore, it was "considered difficult from the perspective of the companies' DNA to bring together engineers responsible for conventional plants with the entrepreneurs working on renewables" (U30). Any attempt to develop renewables within the existing business units would have caused "strong resistance" (U22) and would have directly killed the initiative. As all our interviewees stressed, it was therefore "a good decision" (U1) to separate renewables from the conventional business and develop "a new entity where you can foster a new culture" (E5).

Second, forming separate business units and staffing them with external hires was deemed important since *the organization lacked the necessary capabilities to pursue the technologies in the existing units.* Having been slow to embrace renewables, the Big Four had only very limited capabilities and experience in this area. Therefore, setting up dedicated units with a clear mission to explore renewables promised much quicker results than having frontline employees explore renewables as part of their daily routines. As one E.ON manager recalls, "We set it up outside the normal E.ON organization because we wanted it to be fast and efficient. […] For example, we have a different HR structure, employees cost less, we have younger employees, the teams are smaller, we have a smaller overhead, etc." (U19). An RWE manager agreed that "it was important to start the new business without all the legacy, the personnel processes, and the bureaucracy. Therefore, we decided to form a new unit" (U28).

Third, specialization of employees and top-down integration by management were deemed appropriate because the *environmental opportunities were few and relatively clear*. As one Vattenfall manager recalled, "[t]he generation side is relatively straightforward. There's maybe five or six, seven [renewable] generation technologies you can use […]" (U14), such as onshore and offshore wind power, solar photovoltaics ("PV"), concentrated solar power, biomass, geothermal, and wave/tidal technologies.

Table 4: Rationales for the approach chosen toward renewable energy

Perceived Environmental Characteristics	Impact on Ambidexterity Approach	Exemplary Quotes
High distance between environmental opportunities and organizational culture and capabilities	Lack of support for new technologies in existing units requires separation	"There's no culture that would allow engineers to say, 'Hey, we'll take a few conventional plants offline. And then we'll save the company by developing renewables instead.' Forget it. I believe that when you notice as a firm that you don't have the power to develop it from within, then a more inorganic, separate setup is useful." (U29) "And it was probably useful to set up a separate, legal entity. Because in the existing business that's successful with conventional plants and that sees renewables as a threat […], the new business probably would not have grown that much." (U9) "And therefore we chose a separate entity, which directly reports to the executive board. I believe that this is a reasonable solution, since people would strongly resist the new topic otherwise." (U20) "Then we said—which was a wise decision—that we'd found a subsidiary, since we wouldn't get this done with the normal people in the company. That's a question of will, a cultural question and so forth." (U14) "In 2007, it was a cultural challenge. […]. If I had not had Innogy as a separate entity, but had integrated it into RWE Power, there would have been the danger that the business would not have been able to survive; [it] would have been crushed by the conventional business." (U19) "Cannibalizing your own business—that's always an issue that plays a role in such large organizations. And I think that's something you can only fix if you develop something new in parallel. That's what we tried with [RWE] Innogy, or what BMW tries with its i Series." (U22) "The business culture in the renewable setting is significantly different from the one in conventional technologies. It is a question of speed of decision-making, whether you would be able to excite people within the conventional units [about renewables] and whether [people working on renewables] would feel comfortable. All of this led to the decision to separate the renewables." (E1)
	Lack of capabilities for new technologies in existing units favors separation	"I believe it was a very wise decision, whoever took it, to set our unit up as a separate legal entity that gets its expertise and experience from the renewable energy market." (U28) "I need new processes etc. I can't just do it with the routines of a large corporate; I need to have employees explore things. On paper, this is definitely the right approach." (E10) "Of course this is also a matter of building competences, both in project development and operation. We need to generate added value and reap optimization potential, both of which have to do with bundling competences." (U12) "But when you start such a business, you want to try and keep bureaucracy small and decision processes lean. That's very positive, absolutely." (U28)
Few and relatively clear environmental opportunities	Allows quick, top-down decisions and specialization of employees	"I believe that, when I look back to 2007, one could quickly write down a list of fewer than five technologies, maybe plus geothermal and such things. You could say relatively quickly: 'Let's focus on five or six.' That wasn't rocket science." (U12) "And you needed three attempts and then you could narrow the five or six options down to three." (U12) "PV has been available for a long time and wind, I remember well, has also been around since the 1980s. What we experienced was an improvement of the efficiency of the plants, economies of scale, learning curves […]. But you didn't need to sit for 60 days in an

	incubator and develop new business models. Those are developments that have taken place over many, many years." (E15) "When you talk about large renewables, this is not so much about piecemeal competition in your own backyard. [...] You need more central decision-making, more of a project approach than in decentralized energy."(U19)

In fact, in several of the companies, such as RWE, the choice of technology was made by the management even before the unit was set up, based on personal experience and a superficial evaluation of alternatives. Among the seven main technologies available, offshore wind power was perceived to have the largest synergies with the conventional business as it involved "developing large-scale, central plants, building large assets" (U19). Consequently, all four firms strongly focused on this technology at the expense of others. The limited number of opportunities allowed managers to get a "central understanding of our portfolio of options" and "take central decisions about where to invest the funds" (U2). As a result of these top-down decisions and the clearly separated setup of the new units, all four electric utilities were able to quickly expand their activities in renewable energy. For example, between 2008 and 2013, RWE and E.ON alone invested more than USD15.1B in renewable energy projects. By 2015, renewables already made up 16% of the revenues and more than 50% of the profits in RWE's power-generation business.

The exception: Geographic location and scope influence ambidexterity approaches

While we embarked on our investigation expecting sharp contrasts between the companies, the previous section shows that all four took the structural ambidexterity approach to renewables. Only at EnBW was the renewable business more closely integrated: Whereas the engineering and construction of renewable plants was done by the separate unit, their operation and maintenance was integrated with conventional plants. According to several interviewees, this was because EnBW's exposure to the renewable market differed from its peers'. Since EnBW was only active in one of the 16 German states, it had a more local focus, which created a greater potential for synergies between the conventional and renewables businesses. As one manager of the company stressed, "We are concentrated. Most of our plants are in Baden-Wuerttemberg, and therefore, it pays off to do this integration. The distances are short, so you can generate financial benefits if you do it this way. I believe that, for example, E.ON, with plants in Bavaria and Lower Saxony, would have many more difficulties pursuing such an approach" (U5).

4.2 The second challenge: going downstream

Even as the utilities expanded into renewables, the energy sector was struck by several developments that challenged the incumbents' position once again. First, the continued political support of renewable technologies led to a steady rise of electricity generation capacity, which resulted in a "collapse of market prices" (U9) in the German electricity wholesale market (see Figure 2). Previously, utilities had predominantly relied on electricity generation for earning reliable profits at the level of around 15%. With the increasing share of renewable power, which entered the market at zero variable cost, “the profit margins in the conventional business were completely eroded” (U12). From being the “bread-and-butter business” (U29) that built the companies’ foundation, conventional generation became “an economic basket case” (U29), with companies “having to write down many of the assets” (U29). The political decision in 2011 to phase out nuclear power definitively further reduced the scope for easy profits from depreciated plants. Companies were “shocked […] that they had to phase out their best nuclear plants. […] They were really paralyzed” (E3).

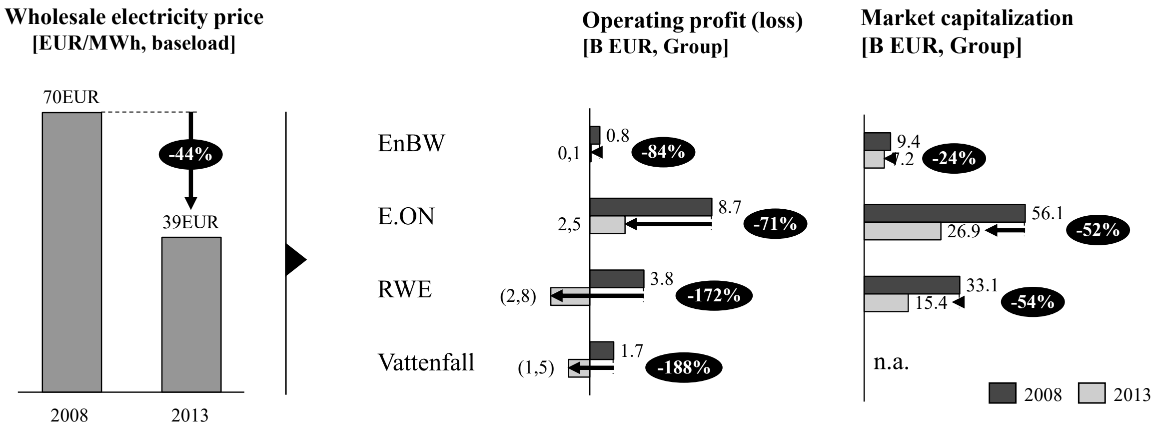

Figure 2: Development of the wholesale electricity price, operating profits, and market capitalization of the “Big Four”

Second, many new downstream technologies that allowed consumers to generate their own electricity, as well as monitor and reduce their electricity consumption, began penetrating the market. For example, due to politically induced mass deployment, costs for residential PV systems “fell drastically” (E10) by almost 50% between 2010 and 2013. As a result “within a very short time […] electricity from small PV systems became cheaper than electricity from the plug” (E10). By 2012, 1.3M German households and firms were already generating their own electricity, implying a considerable loss in sold electricity for the incumbent electric utility companies. As one manager reported, within the utilities, this trend “triggered discussions like, ‘Whoops, help! […] This is a huge market and we’re not participating. Prices have come down and somehow we aren’t part of the game’” (U28). As another manager concurred, “When it all started, we said, ‘That’s too expensive, that doesn’t work.’ Now we see the incredible disruptive potential of PV, simply due to the constantly falling costs” (U12).

The trend toward self-generation was further spurred by the increasing profitability of energy storage technologies that allowed private consumers to considerably reduce their electricity bill and even “completely get rid of their grid connection eventually” (E10). In addition, new digital, smart-home, and energy-efficiency technologies allowed companies to offer new products and services that saved consumers electricity and created a completely new user experience. As two managers summarized, "The energy world is becoming more decentralized" (U15), and "margins are moving from the conventional generation business to the downstream business" (U13).

Together, lower margins on generation and the emergence of new downstream technologies fundamentally challenged the utilities' existing business models. Revenues declined considerably, and the four leading firms' market value plummeted by between 24% (EnBW) and 54% (RWE) between 2008 and 2013. Despite these clear economic signals, it took the Big Four a long time to finally face up to the altered reality of their business environment. This was due to "a combination of missing capabilities and a very strong [cognitive] frame stuck in conventional, centralized generation, which only broke very late" (E2). Two experts expressed that "traditionally, the business of the electric utilities was to take a lot of money and build a huge asset that generated revenues for a very long time" (E9), and that the business logic of all utilities was "clearly aligned with the central generation business; the understanding of decentralized models was missing" (E1). A utility manager we interviewed admitted that, "We are simply really bad at developing and producing products that are tailored to the customer" (U24). However, since it became increasingly clear that the "companies could no longer earn money with the traditional business" (U18) and there was an increasing threat of new entrants, such as Google, around 2011 the utilities started to look for new opportunities downstream in the electricity value chain.

The approach: hybrid ambidexterity

Interestingly, the utilities' approach when entering "new downstream" differed sharply from the one they had used for renewables. Rather than assigning the new activities to new business units, all four chose approaches that combined elements of structural and contextual ambidexterity. In particular, we identify two types of what we label hybrid ambidexterity.

First, RWE, E.ON, Vattenfall, and EnBW used structural and contextual ambidexterity at the organizational level in a parallel but isolated way. All four firms created business units dedicated to downstream technologies, following the structural ambidexterity approach: RWE formed "Effizienz," E.ON "Connecting Energies," Vattenfall "Customers & Solutions," and EnBW "Sales and Solutions" (see Table 5). Like the renewable units, these were clearly separated from the rest of the organization and "given a specific budget, where we can say, 'We want to work on this and that topic'" (U17). Employees were "deliberately recruited from different industries [...] to preserve some distance from the classical electric utility" (U17). Hence, the role of top management was to provide the necessary resources and protect the unit from being swallowed by the conventional business. In the case of RWE Effizienz, for example, one manager said, "I don't believe we would have got this far, if Mr. Grossmann [CEO] had not founded RWE Effizienz rather than relying on all the little activities that were taking place in the company" (U17).

At the same time, all four firms launched comprehensive cultural change initiatives throughout the entire organization. In line with the concept of *contextual ambidexterity*, the goal was to enable and motivate employees to flexibly switch between exploration and exploitation in their daily work. Rather than working on new technologies full-time, staff were encouraged to reflect on their established routines and break out of them when necessary. As one manager observed, "It has to come from the bottom, the conditions need to develop, so that the entire organizational culture changes. [...] There needs to be the willingness to quickly respond to ideas and external changes" (U12). Another manager stated that the goal of the cultural initiatives was to "find the right balance between flexibility and rigidity. On the one hand, to have milestones and goals that define our focus and allow us to push things and deliver. On the other hand, to leave some freedom, freedom to develop new ideas, freedom to explore things, to test things and make mistakes" (U9). Closely in line with the literature, the management's task was to provide the context for this new way of working. In several companies, the cultural shift was promoted by hiring new CEOs who put culture high on their agenda. At RWE, for example, Peter Terium, who succeeded Juergen Grossmann, was soon nicknamed "Esoterium" for putting a strong emphasis on cultural initiatives. One manager, for example, reported spending "10 days in seminars together with other managers, where we practiced things like mindfulness, yoga, and different formats of how to communicate with each other. [...] And this leads to people interacting with each other in a more relaxed, more honest, faster way—that's cultural change" (U9).

Second, all the utilities except Vattenfall *drew on approaches that merged ideas of structural and contextual ambidexterity in one organizational initiative*. RWE, E.ON, and EnBW formed units that, on the one hand, were separated from the existing business and possessed a distinct culture but, on the other hand, flexibly involved frontline employees, thereby providing them with an opportunity to switch between exploration and exploitation. For example, RWE first created the idea competition "Jump!2011," and later the "Innovation Hub," as part of which frontline employees were given time to explore innovative ideas they had come across in their daily work. Every Thursday, small teams of two or three employees could pitch an idea to a jury, the so-called "board of four," which decided whether the team would be given the time and funding to pursue the idea further. Similar initiatives were launched in the form of EnBW's "InnovationCampus" and E.ON's ":agile accelerator". In addition, E.ON created the "Digital Transformation Unit," a task force specifically dedicated to exploring digital technology.

All these initiatives pulled in frontline employees from the old business units and created spaces for them to "work on new projects outside the box" (U26). In contrast to a purely contextual approach, however, the utilities also created new organizational entities that provided a platform for generating ideas, as well as separate organizational structures for pursuing them further. Using the biological analogy of an amoeba, one RWE manager described their Innovation Hub as "a network organization. We are a platform. We have a very fluid structure that allows us to quickly take on new topics and absorb them" (U15). A consultant described the new downstream units as "organisms that are not centrally organized, but allow for heterogeneity, and are more flexible and quick to respond to market changes" (E5).

Top management played a mixed role in these initiatives. On the one hand, it created and protected the initiatives to ensure a sufficient supply of resources. It also provided strategic guidance on the topics to be pursued. As one manager stressed, "top-down support is important, as the initiatives work with different processes" (U26). On the other hand, once created, the initiatives had considerable autonomy in choosing which technologies, products, or business models they would investigate. Management then mostly served to provide the context necessary to ensure a steady supply of ideas and human resources. As one manager explained, in order to help the initiatives succeed, "I need to do everything to create an environment that fosters idea generation, but also enhances the ability to quickly bring products to the market as pilots and test them" (U15). However, as the manager also pointed out, this environment was not present from the start: "the topic of innovation would have been immediately killed by the firm's 'antibodies' if we'd put it on the agenda right away. It took us two and a half years to build the foundation" (U15).

Summarizing our findings, Table 5 categorizes the firms' initiatives for new downstream into structural and contextual ambidexterity, using the criteria introduced in Table 1. It shows that, in contrast to the initiatives for renewable energy, some of the initiatives for new downstream clearly fall under the category of contextual ambidexterity. Moreover, all the firms except Vattenfall set up initiatives that merged features of contextual and structural ambidexterity. Backing up the information presented in Table 5, Table A.2 provides detailed evidence for the categorization of initiatives from our interviews.

Table 5: Firm initiatives to address the challenge of new downstream technologies

Firm	Initiative	Launch	Activity	Structural ambidexterity			Contextual ambidexterity		
				Ex/ex separated	Employees specialize	TMT integrate	Ex/ex not separated	Employees switch	TMT set context
RWE	Effizienz	2009	NPD and sales unit for B2C solutions	X	X	X			
	Innovation Hub	2014	Business model innovation platform	X		X		X	X
	Jump!2011	2011	Idea competition	X				X	X
	Cultural Change	2011	Cultural change initiative				X	X	X
E.ON	Connecting Energies	2012	NPD and sales unit for B2B solutions	X	X	X			
	Digital Transformation Unit	2014	Digital task force	X	X		X		X
	:agile accelerator	2013	Internal start-up accelerator platform	X		X	X	X	X
	Cultural Change	2010	Cultural change initiative				X	X	X
Vattenfall	Europe Innovation	2010	Unit for business model innovation	X	X	X			
	Customers & Solutions	2014	Sales unit for B2B solutions	X	X	X			
	Cultural Change	2011	Cultural change initiative				X	X	X
EnBW	Sales and solutions	2013	Sales unit for B2B solutions	X	X	X			
	Innovations Campus	2012	Internal start-up accelerator platform	X		X		X	X
	Cultural Change	2012	Cultural change initiative				X	X	X

The rationale: exploring a large number of uncertain opportunities

So why did our four firms choose hybrid ambidexterity when exploring downstream technologies? Our interviews show that it was due to the fundamentally different environment they were facing when going downstream compared to going green (see Table 6). As with renewables, the environmental opportunities in new downstream were considered to be distant from firms' culture and capabilities. However, whereas the opportunities in renewables were few and relatively clear, the opportunities in the new downstream business were numerous and uncertain. As one E.ON manager pointed out, it was far from clear which new downstream technologies, products, and services might turn out to be viable:

> *My impression is that new downstream is not that simple. If we just start with the question: "What is the role of electric mobility, and what role is it going to play?" That is already a very broad field. And then you can start thinking about storage or smart applications and smart home. Each of those is a broad field, because if you look into storage, you can say: "What exactly are we talking about—batteries or power to heat?" [...] It is an incredibly broad field. (U12)*

In addition, moving outside the well-known generation market implied a search not just for new technologies, but for entirely new business models, which brought more complexity. As an expert noted:

> *These days, you can't make sense of anything. You have a vague idea how the new energy world and a smart home works. But you have no idea what a business model could look like. You don't know what the products, what the markets are. You don't know what your value chain, your value added, your revenue structure is. You just don't know it today. In the case of [renewable energy, such as] PV, a wind turbine, or biomass, all that is 100% clear. (E15)*

To deal with these myriad potential opportunities, the firms had to rely on an open search strategy that included *distributed decision-making and leveraging the attention and expertise of frontline employees*. For example, one manager stressed that "we are in a dilemma: We currently don't know what the answer will look like. Therefore, I think, we need to focus on staying broad enough in our approach" (U12). Rather than an individual manager selecting among a limited set of opportunities, as was the case for renewables, utilities thus relied on the distributed attention of their employees. One EnBW manager, for example, expressed that:

> *In new downstream you cannot measure the business case from the start, with all the uncertainties. Instead, you only know it once you have learned more in the pilot phase, when you are in the market, when you know what the customer is willing to pay. [...] And this is also why I said, "We need a different space where I have a different process setup that suits the distributed nature and the risk of the business." (U20)*

Table 6: Rationales for the approach chosen toward new downstream technologies

Perceived Environmental Characteristics	Impact on Ambidexterity Approach	Exemplary Quotes
Large distance between environmental opportunities and organizational culture and capabilities	Lack of support for new technologies in existing units requires separation	"And what becomes more important, and what's difficult for us, is customer orientation. I mean, looking at the needs of the people in the market. This is something that utilities are not used to traditionally. We always said that it just wasn't part of our DNA." (U30) "When we started with the renewables, started the wind business, it was clear that we couldn't do it in the conventional business, which thinks very differently. That's why we founded the renewables unit to enter the wind business. Today, you basically have to do it the same way, do it externally or create a new unit that is not caught in the old structures." (U14) "You know as well as I do how difficult it is to suddenly develop new business models [...] that are partly disruptive in the existing organization, in a culture that has been shaped by a different business model over decades. I would say that doesn't work." (U20)
	Lack of capabilities for new technologies in existing units favors separation	"The starting point is not that we do old things better. The starting point is that we do something completely different. And for this, we need a different crew and a new way of thinking." (U21) "The classic renewable business has been located in the core business of EnBW for a long time, and is also part of the generation strategy. What is behind 'new downstream' has a lot to do with new roles and new business models that all have the characteristics of being highly distributed, having small margins, where you reach an interesting profit situation only through mass and summing up the parts. This is why, I think, we need a different setup for this. [...] To develop a business model with a small profit margin [...] we decided to use start-up methodology exclusively, and develop it in a space where we can tolerate mistakes, where we can experiment and maybe one or two out of 10 [ideas] make it." (U20) "We don't use the processes [of the main organization], since we're developing something completely new here—not only technologically, but also with regard to the business models." (E15)
Numerous and uncertain environmental opportunities	Requires distributed decision-making and leveraging the attention and expertise of frontline employees	"I believe that the topic of new downstream is more difficult than the question of upstream, since we are looking into a huge crystal ball and you really don't know which direction it will go in. And that's why at ENBW we formed this new innovation center in which we continuously probe new business models and develop new ideas, bring them to market and see if they work or not. And I believe you need an incredible breadth at the moment to recognize the trends and developments that will confront us in the downstream business and be able to partake." (U23) "In the case of renewables, one deliberately took the decision to set it up as a separate unit with a separate culture, in a positive sense. But now we noticed that it isn't enough to have small, innovative units, since change becomes 'business as usual.'" (U21) "Back then, we said, 'We have conventional power generation and, oh, damn, there's an opportunity in renewables that we might miss.' Therefore we quickly had to use a structural approach. And now, we say we want to redirect the entire organization toward the customer [...]. And you can only do that if you use a contextual approach, which involves a real cultural change. This takes some time, but you need this approach since the opportunities are not as clearly defined, ok?" (U24) "If we're heading for a world where it's not about just producing kilowatt hours but where customers produce their own electricity, then we need a new business model where we are close to the customer. In this case, it doesn't help me if I set up a central unit and

	say 'Now, let's do decentralized energy.' I have to be very, very close to sales. [...] They know the market, they know what's going on and how the customer rules." (U19) "And at the moment there's a lot of change taking place related to [new downstream topics such as] digitization, concepts for energy saving, regionally distributed generation, and storage. And there's just an incredible level of uncertainty with regard to what energy supply will look like in five or 10 years. And that's why we need to position ourselves broadly to be prepared for different trends, different scenarios, and paces. And that's what I mean with 'search'—it's more of a trying out, staying broad, to have the right business model at the right point in time." (U23) "I believe that the customer business [downstream] is much more diffuse than the business with the renewables. [...] That's why we have this large funnel where you throw in a huge number of ideas, try to test them quickly, build the first prototype and filter quickly. [...] If you do it this way, you need to believe that in the market it's far from clear what the winning solution will be [...]. And in the large-scale renewable business, in the end we're project developers. We don't develop the turbines, nor the new business models around them. [...] That's not rocket science. [...] The business model is extremely clear. In the [downstream] customer business, that's different, right?" (U24)

An E.ON manager concurred:

> *I don't believe that you can centrally tell people how they should do their business, but that the frontline employee, who works at grassroots level as an installer, foreman, or manager, has a better understanding of local needs.*

Tapping into the ideas and initiative of employees, however, required a culture of bottom-up idea generation that fundamentally differed from what the utilities had developed in their decades of operating in a monopolistic environment. The bottom-up approach included exactly what have been described in the literature as elements of contextual ambidexterity. At the same time, the companies did not choose a pure bottom-up approach, but made simultaneous use of structural elements. This was done purely because relying on cultural change would have taken too long, and engendered highly dispersed, uncoordinated exploration initiatives. Therefore, besides fostering a broader context for ambidexterity through cultural change, the management used structural means to create dedicated units, giving them a strategic mission to develop new downstream technologies and business models. As one RWE manager emphasized, "we deliberately do not use some of the processes and systems that we have in the company. That would make us too slow" (U15).

While it seems too early to judge the effectiveness of the initiatives the utilities started in the area of new downstream, several managers revealed that the firms had started many promising projects that would play an important role in ensuring the utilities' future survival and performance. As an RWE manager pointed out, "This isn't a youth research competition or a hobby—10 years from now we are expected to contribute a significant share of the future EBIT. That's the framework we have been given" (U15).

The exception: Geographic location and scope influence ambidexterity approaches

As in renewables, all four firms acted surprisingly similarly in response to the challenge of new downstream. The single exception, Vattenfall, did not make use of organizational designs that combined structural and contextual elements. We find that this difference can largely be explained by differences in the firm's geographic location and scope, particularly its exposure to environmental discontinuities and opportunities.

According to a manager, Vattenfall had its largest customer base in the cities of Hamburg and Berlin. In these cities, however, the potential for customers to generate their own electricity by putting PV on their rooftops was clearly limited, as most people lived in rented apartments. As one manager explained, "Berlin and Hamburg are simply not locations where there is great demand for PV. That's simply not the case" (U13). Moreover, Vattenfall Germany is a subsidiary of a Swedish company that only partly operates in the German market. As a consequence, Vattenfall had seen not a decline in customers, but a rise, lessening the urgency of exploring downstream technologies. One manager, for example, noted that "at our parent company, they are still living a bit in the old energy world, as it was here 10 years ago. [...] The disruptions that we see here, they don't exist up there. They build a wind power plant once in a while, but PV doesn't play a role; they don't have the self-generation and the trend toward distributed power" (U14). As a result of this different exposure, Vattenfall could rely on more time-consuming cultural change and faced less of an incentive to set up initiatives that merged elements of structural and contextual ambidexterity. The lack of joint hybrid ambidexterity, however, also meant that Vattenfall showed the least activity among the four utilities in developing new downstream business models and technologies, e.g., in the field of PV. As a Vattenfall manager admitted, "In the area of new downstream, the other utilities were much faster than us. Both E.ON and RWE are much better positioned than us, to be fair. [...] But we are going to launch [a new idea competition] this year."

Emerging theoretical framework

Figure 3 shows the emerging theoretical framework that describes how the environment shapes incumbents' use of structural and contextual ambidexterity. Our study provides evidence that the relative focus on either structural or contextual ambidexterity depends on the nature of the environmental change a firm faces, specifically (a) the perceived distance of new opportunities from the organization's culture and capabilities, and (b) the perceived number and uncertainty of (potential) environmental opportunities. If the perceived distance of new opportunities in the business environment from the existing culture and capabilities of the firm is high and (potential) opportunities are few and relatively clear, this favors the use of *structural ambidexterity*. This is because marked differences between the new opportunities and the existing culture and capabilities may prohibit the exploration of such opportunities in existing units, requiring structural separation. Especially if change is rapid, firms generally do not have the time to adjust their culture and capabilities to the new opportunities, such that setting up new units becomes necessary.

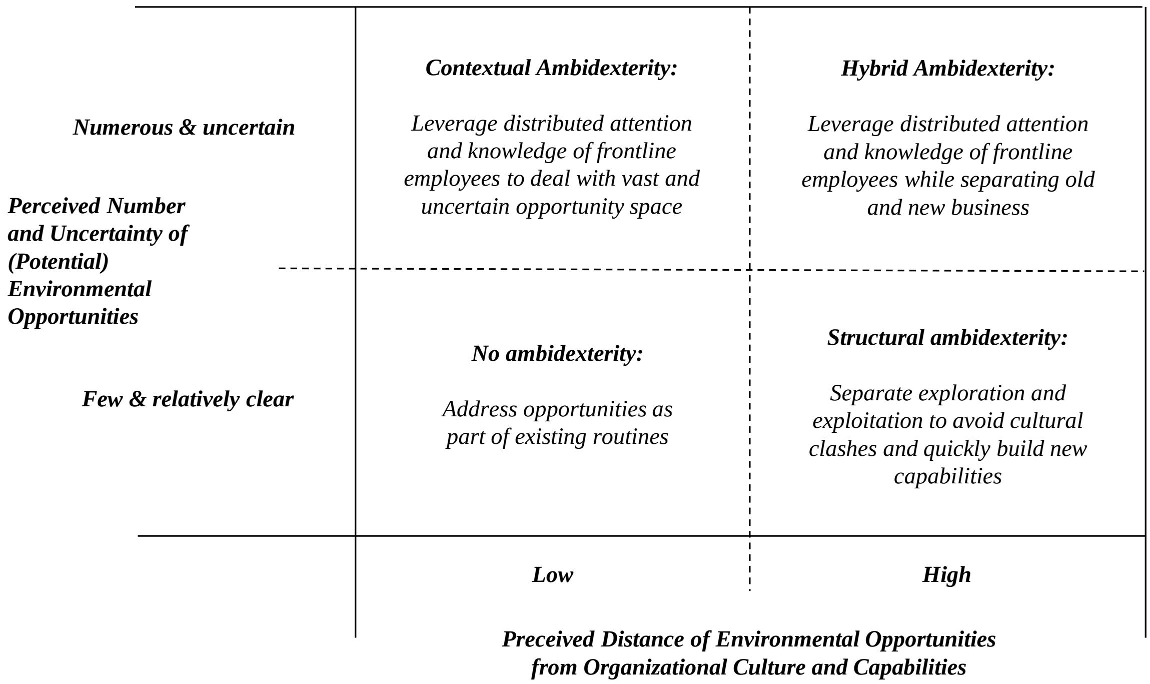

Figure 3: Emerging theoretical framework describing how perceived environmental characteristics influence firms' ambidexterity approach

Contextual ambidexterity, in turn, allows firms to leverage the expertise and knowledge of their entire workforce. We find that our sample firms therefore shifted their focus toward contextual ambidexterity whenever the perceived number and uncertainty of (potential) opportunities in their environment was high. In such a complex, uncertain environment, contextual ambidexterity allows for bottom-up scanning of opportunities without having to set up a unit with a dedicated vision or technological scope that might narrow a firm's search unnecessarily.

Our study shows that when opportunities are perceived as being numerous/uncertain *and* as requiring a different organizational culture and capabilities, organizations draw on what we label *hybrid ambidexterity*, i.e. a combination of structural and contextual ambidexterity. In particular, we identify two hybrid approaches: Organizations may use structural and contextual approaches in parallel but separately, an approach we label *split hybrid ambidexterity*. Alternatively, organizations may draw on organizational forms that directly combine elements of both structural and contextual ambidexterity, an approach we label *joint hybrid ambidexterity*.

Finally, our study also provides some evidence that the balance between structural and contextual ambidexterity is influenced by firm-specific factors. We find that a firm's balance between structural and contextual ambidexterity is shaped by its geographic location and scope, which influence whether managers attend to environmental discontinuities and how distant they perceive emerging opportunities as being from the organization's culture and capabilities. In this sense, the choice of ambidexterity modes portrayed in Figure 3 is by no means deterministically linked to environmental changes, but strongly depends on managers' perception of environmental opportunities.

5 Discussion

5.1 Implications for the literature

Our study makes at least three contributions to the literature on ambidexterity. First, we show that the choice of a given ambidexterity approach strongly depends on the nature of the environment that an organization faces. The previous literature has studied the antecedents of ambidexterity as a whole, but provides limited insights into why companies would invest in structural vs. contextual ambidexterity (Lavie et al. 2010; O'Reilly and Tushman 2013). Addressing this gap, we investigate the determinants of a firm's balance between structural and contextual ambidexterity. We find that when new opportunities in a firm's environment required a fundamentally different culture and capabilities but were few and relatively clear, firms drew primarily on structural elements when trying to become ambidextrous. This is because structural ambidexterity involves creating separate business units, which allows firms to maintain different sub-cultures concurrently. At the same time, the limited number of clearly identifiable technological opportunities lets managers pursue a top-down approach to balancing exploration and exploitation. Conversely, if the array of opportunities in the firm's environment is vast, open, and uncertain, this favors a more contextual approach to ambidexterity, which leverages the attention, knowledge, and capabilities of frontline employees throughout the organization. When the firm's environment is characterized by opportunities that are both distant in terms of capabilities and culture *and* large in number and uncertain, firms can combine elements of contextual and structural ambidexterity.

By identifying a number of environmental characteristics that influence firms' approaches to ambidexterity, our research answers recent calls to disentangle the different dimensions of environmental dynamism (Birkinshaw and Gupta 2013; Junni et al. 2013; Markides 2013). Moreover, our observations are in line with previous research stating that "it is harder to see how [contextual ambidexterity] would permit a company to adjust to disruptive or discontinuous changes in technologies and markets" (O'Reilly and Tushman 2013, p.329). In fact, we find that structural ambidexterity is better suited to deal with environments that require fundamental shifts in capabilities and culture, but that contextual ambidexterity may be needed in those cases where firms need to rely on the distributed attention and "hive mind" of their frontline employees. In this sense, our research links to the work on organizational networks, which has shown that "diverse ties might help the organization access quality information to recognize opportunities and/or threats hidden in a complex environment" and that "with sources of expertise that are widely dispersed, network ties tend to become salient predictors of the organization's innovation performance" (Simsek 2009, p. 615; see also Powell et al., 1996). Broadly speaking, our findings are therefore in line with the literature on strategic fit (Hambrick 1983), which suggests that firm performance strongly depends on firms' ability to achieve congruence between organizational variables (such as structure) and environmental contingencies.

Second, we provide systematic empirical evidence on how firms combine structural and contextual ambidexterity. Several scholars have suggested that firms may not draw on either structural or contextual ambidexterity exclusively, but may use the two types concurrently (Kauppila 2010; Raisch and Birkinshaw 2008). However, so far the literature has predominantly studied structural and contextual ambidexterity in isolation, precluding any conclusions about how they are combined in practice. Our study provides empirical evidence on how firms combine elements of the two approaches to leverage their respective advantages, an approach we label *hybrid ambidexterity*. We identify two types of hybrid ambidexterity. *Split hybrid ambidexterity* involves using structural and contextual approaches at the same time but in an isolated way. For example, firms may set up distinct business units to enter new organizational fields while simultaneously engaging in cultural change initiatives that enhance the firms' contextual ambidexterity. *Joint hybrid ambidexterity* consists in using new organizational forms that merge individual elements of structural and contextual ambidexterity. Such new organizational forms can be found in loose network structures or permeable venturing units that separate exploration and exploitation activities yet also allow frontline employees to flexibly join and leave exploration initiatives. By identifying initiatives that cross different levels of analysis, our research demonstrates the merits of studying ambidexterity as a multi-level, nested phenomenon (Birkinshaw & Gupta, 2013: 293f). Moreover, our research suggests that firms do not only strike a balance between exploration and exploitation, and between different modes of exploration and exploitation (such as internal R&D, alliances, M&A), but may also balance different types of ambidexterity. In this context, joint hybrid approaches may be particularly well suited if the pace of environmental change is high, since split hybrid approaches can be assumed to take longer to implement.

Third and finally, we show how firm-level factors influence the relationship between environmental discontinuities and firms' ambidexterity approach. We find that, generally speaking, all firms reacted similarly to the two major environmental changes during the time of interest, which indicates a significant role for environmental as opposed to firm-level factors. Yet, we also find differences in the timing and design of ambidexterity approaches across firms. We identify a firm's exposure to environmental discontinuities resulting from its geographic location and scope as the main explanation for these differences. In doing so, we explicitly contribute to the literature on organizational adaptation and change, highlighting space as an important mediator between environmental change and firm responses. Previous work predominantly assumes environmental discontinuities to affect all firms in an industry to an equal degree. We show that firms within the same industry may differ significantly with regard to their geographic focus, which may come with important implications for the need and ability to respond to environmental jolts. Our findings imply that firms that are less exposed to specific environmental discontinuities may be less inclined to adjust their organizational structure. While this seems reasonable from a management perspective, it also creates a risk for multinational firms that face discontinuities in only a few of their country markets. Particularly if a firm's headquarters is located in a country that is not exposed to environmental discontinuities, this may delay its response in regions with higher exposure, impairing firm performance.

5.2 Limitations and future work

Our study has several limitations. First, since it is based on an in-depth observation of four firms in the electric utility industry, it remains open to what extent our findings are generalizable to incumbent organizations in other sectors. To scrutinize the external validity of our findings, we conducted interviews with experts from the banking and manufacturing industries, which suggested that many of our findings might be applicable to other sectors. Still, the electricity sector is idiosyncratic in that is highly regulated and was only recently opened up to market competition. Future research should therefore analyze the use of structural, contextual, and hybrid ambidexterity in other sectors to identify potential contingencies.

Second, additional research is needed that investigates the role of isomorphism in firms' ambidexterity approaches. Our study provides direct evidence that the design of ambidexterity approaches is linked to the nature of the firms' environment and that differences in exposure to environmental discontinuities lead to differences in firm responses. Yet, given the strong similarities in firm approaches, it seems possible that firms at least partly emulate each other's approaches when reacting to the same environmental shock. When asked whether this was the case, our interviewees stressed that they did not pay much attention to their competitors and designed their approaches according to best practice in other sectors. Still, future research should investigate how competitive dynamics and imitation might moderate firms' choice of ambidexterity approaches in times of environmental discontinuities.

6 Conclusion

This study addressed the question of how the environment shapes incumbents' use of structural and contextual approaches to ambidexterity. Studying how four major incumbent electric utility companies reacted to two major environmental discontinuities, we show how firms combine structural and contextual elements, and what drives the balance between the two types of ambidexterity. By introducing the notion of hybrid ambidexterity, our work fills a chasm in the literature on ambidexterity, which has mostly treated the two approaches in isolation. Our case descriptions show that, in practice, structural and contextual approaches are combined by organizations in many ways to accommodate specific environmental demands. Yet, we see our study as just the first step toward a better understanding of the many conceivable ways in which firms "live" ambidexterity. In this sense, we hope that our work inspires future research that takes a closer look at organizational designs that firms can use in their quest for hybrid ambidexterity.

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Appendix

Table A.1: Evidence for the categorization of firm initiatives for renewable energy

Firm	Initiative	Ex/Ex separated vs. not separated	Employees specialize vs. switch	TMT integrate vs. provide context
RWE	Innogy	Separated: "And [Innogy] had deliberately been set up in a way that it was not a department in the larger company, but a separate legal entity." (U28)	Specialize: "But we did not transfer people from the conventional generation business to the new unit to use their experience or know-how." (U4)	Integrate: "The role of top management was to secure funds [for Innogy], so they could build the projects." (U1)
E.ON	Climate & Renewables	Separated: "And therefore we chose an independent entity, which reports directly to the executive board in Düsseldorf." (U30)	Specialize: "The people that I know [in Climate & Renewables], all of them, are all specialized in this area." (U24)	Integrate: "At the end of the day, the top managers of E.ON allocate the budget for Climate & Renewables, especially CAPEX, to give them scope to invest." (U24)
EnBW	Renewables	Separated: "EnBW Renewables GmbH was formed effective 1 October 2008 with the objective of bundling and expanding the group's activities in the area of renewable energies." (EnBW annual report 2008)	Specialize and switch: "We have the category of people who only deal with conventional plants [...]. Then, there's people who deal with both. [...] And then, there's those things that are particular to renewables." (U5)	Integrate: "The core task of the management was budget allocation." (U2)
Vattenfall	Wind	Separated: "Of course, it makes sense to deliberately separate things, to leave the corporate world behind to a certain extent, to nurture a different culture and develop different ways of decision-making." (U7)	Specialize: "Then we said that we would directly found a subsidiary, since it was clear that we wouldn't get it done with the normal people in the company." (U14)	Integrate: "It was not an easy process. At some point, the CEO said: 'I'll just do it, the other managers should quit complaining.'" (U14)

Table A.2: Evidence for the categorization of firm initiatives for new downstream

Firm	Initiative	Ex/Ex separated vs. not separated	Employees specialize vs. switch	TMT integrate vs. provide context
RWE	Effizienz	Separated: "That is covered by the deliberately founded organizational units, such as Effienz GmbH." (E2)	Specialize: "Employees from other industries were an important pillar, which is why we purposefully recruited people from different industries and said that we want to preserve some distance from the classical electric utility." (U17)	Integrate: "We are given a specific budget, where we can say, 'We want to work on this and that topic.' That is part of the regular business unit meetings." (U17)
RWE	Innovation Hub	Separated: "It is a network organization. We structured it according to companies like GoreTex or Kyocera. It is called 'cell structure' or 'cell management' or 'the amoeba principle.' De facto, you give the responsibility and freedom to teams, the smallest possible units, to drive and develop ideas." (U15)	Switch: "And all the people who are interested in these new topics can participate and come to the open platform. There is a lot of communication going on, there are invitations to chats, brainstorming sessions, where everyone can come and pitch in their ideas." (U9)	Integrate: "It is top-down because the initiative is supported and ring-fenced by the executive board." (U15) Provide context: "The topic of innovation would have been immediately killed by the company's 'antibodies,' had we put it on the agenda right away." (U15)
RWE	Jump!2011	Separated: "We did this as an individual initiative. The approach was successful but we didn't anchor it in the organization, as a continuous process." (U10)	Switch: "'Jump' is an idea competition, which was rolled out throughout the entire organization and as part of which the best ideas were awarded. The successful employees were then given the time and financial resources to further develop the idea." (U1)	Provide context: "[CEO] Juergen Grossmann sponsored the initiative. And we had a jury, including a professor from Dortmund who deals with entrepreneurship." (U10)
RWE	Cultural Change	Not separated: "But 'RWE 2015' is much more than this. In the end, it is about further developing the organizational culture. Striving for improvements in processes, structures and business models needs to be part of daily work." (RWE annual report, 2012)	Switch: "That means establishing a culture in which improvement of processes and products and structures are initiated by the employees themselves and do not require orders from 'above.' And this means that the improvements are part of daily business and don't have to be made the subject of 'projects.'" (RWE annual report 2013)	Provide context: "Our managers are ambassadors and multipliers of our organizational culture." (RWE annual report)
E.ON	Connecting Energies	Separated: "We founded a new business unit 1.5/2 years ago [...]. That's called E.ON Connecting Energies. [...] The business unit independently drives the business in this area." (U12)	Specialize: "The unit should work independently of E.ON. The guiding principle is that people should not be kept from doing their work, but should fully focus on what needs to be done [in the unit]." (U24)	Integrate: "A larger budget was reserved for the unit [...]. The focus [of top management] is clearly on budget allocation." (U24)
E.ON	Digital	Separated: "In my previous	Switch: "I don't care where	Provide context: "There's no

	Transformation Unit	role […], I built a separate unit." (U21) Not separated: "Well, it is a network organization, set up as a matrix. We didn't want to create a new, central ivory tower, but a well-connected wire-mesh fence, in a positive sense." (U21)	people sit, what they work on and how they work. […] I gather people and work with people, wherever they are, but I need a core team to build these things here, the networks." (U21)	classic chain, where the CEO initiates things and things are being broken down and just implemented as he said. […] The initiators are often just regular employees. Everyone has the possibility to initiate things, that's the philosophy behind it." (U21)
	:agile accelerator	Not separated: "'Agile' is not a separate organization. It's just, let's say, two to four people who have the right to say which projects are supported. They just need to support the projects, but they don't manage them." (U24) Separated: "The projects [supported by 'Agile'] are completely independent." (U24)	Switch: "It's a modern suggestion scheme. You can hand in your idea, I believe through the intranet, and then there's a sort of contest in front of a jury where the ideas are presented. And if someone gets selected, then these people are released from work for this topic and have some time and budget to pursue their idea." (U12)	Integrate: "The task of the top managers is clearly to allocate budget. I mean, 'Agile' gets money. They need to invest this in projects, i.e., the top management needs to think about which projects to invest in." (U24) Provide context: "It is important that it can run for a while and doesn't get buried under the corporate routines, that someone says: 'We need to have a monthly reporting, performance discussion and all this.'" (U12)
	Cultural Change	Not separated: "I believe that we shouldn't pick any fields or technologies. Instead, I believe that it is better to change the corporate culture, the people and the way they behave in such an environment." (U12)	Switch: "In parallel to the 'E.ON-2.0' program, E.ON is developing a culture that focuses on faster decision-making, quick implementation of decisions, standardization of processes and activities, clear responsibilities as well as keeping in mind the value added for the company as well as the customers and stakeholders." (E.ON annual report, 2013)	Provide context: "Yesterday, we heard from the CEO that we want to be a customer-oriented organization. This means that we have to think and act in a customer-oriented way in every step we take and every sentence we speak." (U21)
	Europe Innovation	Separated: "To achieve Vattenfall's climate goals, the Vattenfall Europe Innovation GmbH was founded at the beginning of 2010. The company will develop new business areas, products, services and technologies in the area of energy technology, energy services as well as related business areas." (Vattenfall annual report, 2010)	Specialize: "Here we have the people working on innovation. We work on something new and then we get together and ask, 'What can we do?'" (U14)	Integrate: "Of course we need money to develop these things, so the budget is essential." (U14)
Vatten-fall	Customers & Solutions	Separated: "What we used to call 'Sales' is now called 'Customers & Solutions.' It is an overarching organizational structure, i.e. Matein Hagen is now responsible for the sales business in Sweden,	Specialize: "That's a separate business area and therefore it's clear that it works more like a silo." (U14)	Integrate: "The top management simply allocates the budget." (U14)

		Finland, the Netherlands and Germany." (U18)		
Vatten-fall	Cultural Change	Not separated: "We have to bring innovation culture into the processes, not just ideas." (U14)	Switch: "We need to further enhance our flexibility by integrating a culture of operational excellence in our daily work." (Vattenfall annual report, 2012)	Provide context: "Of course you can order [cultural change] top-down. But you won't draw anyone through the change curve that way." (U18)
EnBW	Sales and solutions	Separate: "The development of new decentralized solutions is being accomplished in its own business department. We test newly developed business models in sales-oriented field trials in the areas of decentralized energy systems, energy efficiency, smart worlds and electric mobility." (EnBW annual report, 2013)	Specialize: "Sales & Solutions GmbH (SSG), with its EnBW and Watt brands, specializes in the national sale of electricity and gas to major industrial customers, redistributors, industrial customers, SMEs, chains and municipalities." (EnBW annual report, 2013)	Integrate: "Furthermore, €6.8 million or 2.5% of the investment in intangible assets and property, plant and equipment was primarily invested in strengthening sales by expanding the range of services offered as a supplier of decentralized solutions – such as contracting, for example." (EnBW annual report, 2013)
	Innovations Campus	Separate: "The campus is our incubator. It is a room that doesn't smell like corporate and doesn't look like it. It works like a start-up or a boot camp or accelerator. It is far enough from [the headquarters in] Karlsruhe." (U20)	Switch: "And there you'll find people who come from the respective business units, from sales, from marketing, from IT, but also technologies and capabilities that come from start-ups. That's where you meet." (U29)	Provide context: "At the core [the task of the top management] is cultural change. Because if you get stuck somewhere, which happens quite quickly, you need the top management to say that we're doing it because it's important." (U26) Integrate: "Without top management attention, the entire thing wouldn't work. [...] What's important is that I can make my own budgets and finance things out of my own pocket. So, I am not dependent on the business unit; it would be fatal if this was the case." (U20)
	Cultural Change	Not separated: "We want to foster more ideas and creativity from within the company as part of the cultural transformation. There's a large body of knowledge that you have directly in front of you and that you can use in developing your own innovation agenda." (U20)	Switch: "The assessment of corporate culture also suffered downgrades as a result of the new requirement that employees should act increasingly entrepreneurially." (EnBW annual report 2013)	Provide context: "Actions aimed at direct contact between management and employees – for example, the 'Board of Management visits' – have proved to be very useful corporate development tools at some companies, and will be continued. [...] We will significantly shorten our decision-making paths, thereby securing the requisite response speed within a constantly changing market environment." (EnBW annual report, 2013)

Paper III

Invited to Research Policy Special Issue; Under Review

Delineating Policy mixes
Contrasting the Top Down and Bottom Up Approach
along the Case of Energy Storage in California

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Abstract

The interplay between policy mixes and sustainability transitions has received increasing scholarly attention in recent years. Despite numerous empirical and conceptual advances in this literature stream, we still lack guidance when it comes to the reoccurring question of how to delineate the relevant elements of a policy mix in a given context. We address this gap by building on the notion that two archetypical approaches to define the policy mix can be distinguished, namely the top down and the bottom up approach. While the former commonly follows the perspective of a specific governance level or body designing the policy mix, the latter adopts the perspective of the actors involved in shaping the focal transition and being affected by a given policy mix. Based on a mixed empirical strategy, comprising archival data analysis, semi-structured interviews, and a techno-economic model, we conduct an in-depth case study of energy storage policy in California in 2016. Our comparison of the outcome of the top down and the bottom up approach reveals that the suitability of each is contingent upon the specific research design. While the top down approach is well suited to shed light on internal dynamics and the governance structure behind a given policy mix, the bottom up approach is preferable when it comes to analyzing the interaction between policy elements across different domains. Providing a guideline for the initial step of every policy mix analysis, our dichotomy may serve as the starting point for a consistent research program building on the policy mix framework.

Keywords

Policy mix; Policy Design; Sustainability Transitions; Innovation; Technological Change

1 Introduction

In recent years the concept of policy mixes[1] has gained popularity as it explicitly recognizes the complex multi-level, multi-agent interactions that appear to be prevalent among many real-world policy schemes and suggests to assess policy interventions from an integrated perspective (Flanagan et al., 2011). However, while such a comprehensive approach provides the opportunity to shed light on a number of characteristics that are abstracted from when assessing policies on an individual level, it also entails a number of challenges for the process of analyzing and further developing policy mixes. In particular, despite significant conceptual advances in recent years (Rogge and Reichardt, 2016), a constant challenge revolves around the initial step of any policy mix analysis, namely the non-trivial decision about which elements to include in the focal set of policies. A look into the literature reveals that different levels and units of analysis are applied when it comes to delineating both the *scope of policies*, and the *focal domain* these policies attempt to affect. In particular, studies have scrutinized policy mixes both within and across jurisdictions, policy fields, or government entities, shedding light on their impact on various domains ranging from regional economies to individual technologies. While it has been acknowledged[2] that such differences in *boundary setting* have significant implications for the subsequent analytical process[3] and the insights that can be expected from it, we currently lack theory that sheds light on the link between defining and analyzing the elements of a given policy mix. This insufficient understanding is problematic for several reasons. In particular, it may lead to overly *complex or oversimplified* representations of real-world policy mixes, which may undermine the value of the results that arise from such analyses (Flanagan and Uyarra, 2016). In addition, it may foster *implicitness and inconsistency* when it comes to delineating the analytical scope of policy mixes, which may complicate or prohibit the comparison of findings across studies and question their degree of generalizability. In sum, these issues may *undermine the legitimacy* of the emerging research stream building on the policy mix research framework.

To address these challenges, this paper explores and synthesizes different boundary setting approaches found in the literature, thereby providing a common ground for future policy mix analyses. The two archetypical boundary setting approaches that emerge from the literature are the *top down approach*, which delineates a given policy mix based on its *strategic intent*, and the *bottom up approach*, which

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[1] In this paper we follow the analytical framework provided by Rogge and Reichardt (2016) which defines a policy mix as an combination of (at least two) *policy instruments* that is embraced by an overarching *policy strategy*. Building on the taxonomy by Del Río and Howlett (2013), we add that real-world policy mixes often pursue *multiple goals*, and are frequently shaped by multiple *governing entities* spanning across *policy fields* and *multiple levels of public administration*.

[2] "[Of] course, the specification of the system boundaries in terms of the scope of the policy mix to be studied also determines the alleged feasibility of achieving policy mix consistency and coherence" (Rogge and Reichardt, 2016, p. 1630).

[3] Operationalization of constructs; core analysis; presentation and interpretation of results

delineates a given policy mix according to its *actual impact*. Building on this dichotomy, this paper seeks to answer *how the two approaches to delineate a policy mix affect its scope and subsequent analysis*. To address this question, we conduct an in-depth case study of the emerging policy mix around energy storage in the state of California (USA) in 2016. This setting has been chosen since it meets all criteria necessary to make a policy mix analysis applicable and valuable, and it provides a rich empirical basis for inductive theory building. Based on a systematic review of a comprehensive body of archival data, we first derive and contrast the outcome of the two approaches, comprising a set of 66 policy elements (41 strategies, and 25 instruments). Second, we triangulate our findings in 24 semi-structured interviews with policymakers, industry representatives, and academic experts on California's energy transition. Third, to illustrate the combined impact of policy instruments across policy fields and government entities, we elaborate on the economics of three selected energy storage technologies derived from the bottom up approach making use of a techno-economic model.

Our analysis reveals that the top down and the bottom up approach lead to different sets of policy mix elements, governing entities, and processes associated, which in turn, has significant implications for their subsequent assessment. Since both approaches entail specific advantages and disadvantages, they should be framed as complements whose suitability is contingent upon on the individual research design. For instance, by adopting the perspective of the policymaker, the top down approach lends itself to shed light on the internal dynamics and the structural configuration associated to the governance of a policy mix that is coined by a given strategy. By contrast, the bottom approach may be better suited when it comes to uncovering contradictions and barriers between policy elements that arise from coordination challenges between different policy realms, since it builds on the perspective of the stakeholders closest to the technologies which are regarded key drivers of sustainability transitions.

The article is structured as follows. Chapter 2 reviews the policy mix literature, and conceptually introduces the top down and the bottom up approach. Chapter 2.3 outlines key selection criteria that researchers cases to be analyzed by the two approaches should abide by, and introduces the case of energy storage policy in California. Chapter 0 provides a detailed account of the methodology applied and the data being used, on which basis we derive the results that are presented in Chapter 4. Chapter 5 discusses our findings, deriving important implications for future policy mix analyses, before Chapter 0 concludes.

2 Literature Review

2.1 The challenge of delineating policy mixes

Despite recent advances on the concept of policy mixes, one of the key challenges still revolves around the initial step of any policy mix analysis, namely delineating the scope of the focal phenomenon. As Rogge and Reichardt (2016, p. 1630) point out, depending on the research question and case, the underlying boundaries of policy mix analyses "can vary substantially". In other words, there seems to be no universal approach to *appropriate* boundary setting.

But, while it has been acknowledged[4] that boundary setting has significant implications for the subsequent analytical process[5] and the insights that can be expected from it, our understanding of the link between defining and analyzing the elements of a given policy mix remains limited. This is problematic for a number of reasons. First, incorporating too many elements may lead to an overly complex, inefficient analysis, and results that are hard to interpret. Analyzing too few or the wrong elements corresponds to an omitted variable bias, and may lead to results that are based on an overly simplistic portray of real-world policy mixes (Flanagan and Uyarra, 2016). Second, the absence of universal criteria or accepted heuristics for how to delineate policy mixes may ultimately lead to confusion about how to correctly apply the policy mix framework throughout different research settings, which entails the threat of not leveraging its full potential (Flanagan et al., 2011; Rogge and Reichardt, 2016). Third, and perhaps most importantly, using inconsistent sets of policy elements to elaborate on similar research questions may complicate or prohibit the replicability and comparison of results. This, in turn, may question their degree of generalizability beyond the specific empirical contexts investigated. In sum, these issues entail the danger of undermining the value of the scholarly community's intent to develop "policy design theory […] to better inform policy design practice" (Del Río and Howlett, 2013, p. 4). To address this issue, this paper explores different *boundary setting* approaches found in the literature, providing a common ground for future policy mix analyses.

2.2 Deriving a policy mix "top down" via its strategy, or "bottom up" via its impact

The extant body of literature on the policy mix concept shows that two archetypical approaches for *boundary setting* exist. In particular, we find that articles pursue either a "top down" approach, which delineates a given policy mix based on its *strategic intent*, or a "bottom up" approach, which delineates a given policy mix according to its *actual effect*.

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[4] "[Of] course, the specification of the system boundaries in terms of the scope of the policy mix to be studied also determines the alleged feasibility of achieving policy mix consistency and coherence" (Rogge and Reichardt, 2016, p. 1630)

[5] operationalization of constructs, transient characteristics to be studied, methodology, presentation and interpretation of results

Figure 1 illustrates that this dichotomy conforms with the current research framework for analyzing the link between policy mixes and technological change proposed by Rogge and Reichardt (2016).

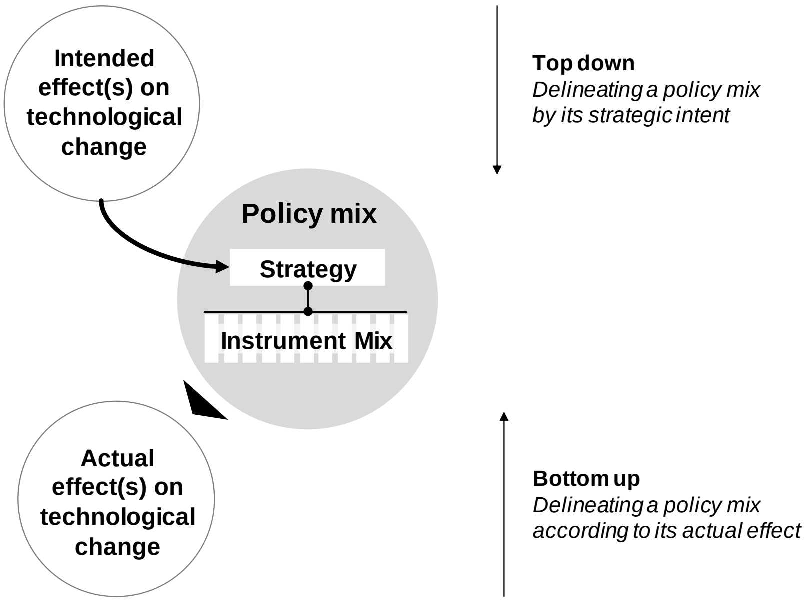

Figure 1: Two archetypical approaches to derive a policy mix: "top down" vs "bottom up" (based on (Kivimaa and Kern, 2016, p. 210) and (Rogge and Reichardt, 2016))

Each of the approaches lends itself to specific types of policy mix analyses, since they entail decisions about the level and unit of analysis. In particular, the top down approach adopts the perspective of the actors in charge of governing the focal policy mix, most importantly policymakers. It builds on the idea that a policy mix can be delineated according to an overarching strategic intent to spur technological change in a specific domain. This notion is picked up by number of studies, for example by Sorrell's (2003) analysis of interactions in the domain of *climate policy* in the European Union (EU), Del Río (2016) who analyzes the *EU renewable generation policy mix*, or by Germany's Federal Ministry for Economic Affairs and Energy (BMWi, 2016) which recently released an overview of EU-level and state-level legislation geared towards governing the country's *energy supply system*. Besides such a broad focus, both regarding the geographic and the thematic scope, there are several studies which select a narrower definition of the common strategic denominator to delineate the relevant policy elements in a top down fashion. Examples include, Kern and Howlett (2009) who focus on the Netherlands, and elaborate on the changing composition of the *national energy policy* mix, Quitzow (2015) who elaborates on the policy mix driving *India's National Solar Mission*, i.e. the country's strategy for promoting solar energy technologies, and Reichhardt and Rogge (2014) who scrutinize *Germany's offshore wind* policy mix. Despite being an analysis of instrument mixes, rather than a policy mix analysis (cf. Chapter 2.3), Del Río (2014) similarly scrutinizes EU policies, but focuses on instruments that are characterized by the common strategic goal of pursuing *renewable energy support*. Independent of the focal level of governance, and the specific research case, many of the studies that apply the top down approach do so in order to elaborate on aspects of vertical and horizontal coordination. In particular, they select a given authority being in charge of governing the focal policy mix (e.g. a national state) and elaborate on aspects such as the interaction between its elements (strategy and instrument mix), the organizational structure and processes associated to its governance, or its emerging characteristics.

While the former studies have provided rich insights into numerous real-world policy mixes by building on the top down approach, many of them deliberately abstracted from policy elements which were not explicitly embraced by the strategic intent in focus of the corresponding study. Hence, policies that did not pertain to the focal policy mix domain under scrutiny, were mostly framed as part of the institutional context of the particular research setting. This can be explained by complexity of real-world policy mixes which translates into a trade-off between comprehensively taking into account all the elements of the core phenomenon, and maintaining a scope that allows for a comprehensible analysis. In this regard, Rogge and Reichardt (2016, p. 1630) point out that "analysts have to decide whether it is sufficient to focus on the policy mix creating the protected space for an emerging sustainable technology or whether they also need to pay attention to the policy mix of the encompassing regime, including, for example, subsidies for competing technologies".

In an attempt to achieve the latter, the bottom up approach adopts the view of the actors who are affected by the policy mix, most importantly the firms that develop the corresponding innovations necessary to put sustainability transitions into practice. It builds on the idea that a policy mix can be delineated according to its actual effect on technological change in a specific domain. Several studies build on this approach, for instance, an international consortium (OECD/IEA/ITF/NEA, 2015) has examined the barriers to low-carbon investments around the world, which yields an overview of misalignments across a *variety of policy domains* (e.g. fiscal, competition, and trade policies). Similarly, Nauwelaers et al. (2009) investigate how *EU policies affects R&D investments*, taking both intentional and unintentional effects into account. Picking up on the aspect of unintentionality, Sovacool (2009) collects a comprehensive list of *policy impediments to energy efficiency and renewable power in the US*, which may be framed as a "negative policy mix". Many of the studies employing the bottom up approach concentrate on the analysis of policy instruments and their effects, thereby regarding the strategic rationale, which the instruments are potentially aligned by or nested in, of second-tier interest. For example, Proudlove et al. (2016) render quarterly reports offering insights into the emerging mix of policies affecting the confined domain of *customer-sited solar PV in the United States*. Since a holistic assessment of the wide range of intended and unintended impacts of a given policy instrument with a range of particular design features is hardly feasible, less so for mixes thereof, bottom up analyses often deliberately narrow down the focal domain under scrutiny, and concentrate on a narrow metric along which the policy effect(s) is measured. For example, Proudlove et al. (2016) focus on the *economic viability* of the aforementioned technology-application nexus, while Murphy et al. (2012) render a comprehensive overview of the policy mix which spurs *investments into energy efficiency in private residences in the Netherlands*.

Our literature review reveals that both archetypical approaches to delineate policy mixes are being used. However, since each study focuses on either of the two approaches, we currently lack an integrated analysis that applies both approaches to the same research setting. This setup would lend itself to assess to which degree the two approaches differ, and which antecedents and implications are associated to their selection. Given the issues associated to the lack of systematic and consistent boundary setting outlined above, this paper seeks to answer how the two archetypical approaches to delineate a policy mix – *top down* vs *bottom up* – affect its scope and subsequent analysis. To address this question, we employ both approaches in an identical research setting and, by comparing the resulting policy mixes, derive implications for theory and practice. This includes elaborating on approach-specific advantages and disadvantages that translate into recommendations for various research designs based on the policy mix framework.

2.3 Research case

Selection criteria

To explore how the two archetypical ways of delineating a policy mix – top down vs bottom up – affect its subsequent analysis, the research case should adhere to the following criteria. First, the setting must render the application of the policy mix framework adequate and valuable. Hence, a minimum requirement is that the policy mix under investigation contains the elements outlined by Rogge and Reichardt (2016, p. 1622ff), namely an *instrument mix*, consisting of at least two policy measures, which is embraced by an overarching *strategic component*[6]. In addition, to render the analysis valuable the elements contained in the selected policy mix should interact in non-trivial ways so that an integrated analysis is required to uncover and address the associated coordination challenges. Two reasonable indicators for such non-trivial policy interactions are the involvement of multiple government entities (hierarchy levels or agencies), or the existence of trade-offs between multiple policy goals (e.g. the support of competing niche technologies). Both of these characteristics translate into a need for vertical or horizontal coordination, which frequently characterize real-world policy mixes (Del Río and Howlett, 2013).

Second, since the top down approach and the bottom up approach build on the *intended,* respectively the *actual effect(s)* of the focal policy mix, the research setting should provide as a *dependent variable* a domain that allows studying both of these aspects. Given that technological change and innovation have traditionally been in the focus of the literature on policy mixes for sustainability transitions, it

[6] The existence of a strategy automatically implies that some entity has the authority over this strategy. This could be a specific government level (e.g. a country's Legislator), a particular government entity (e.g. a Ministry governing a specific policy domain), or an alliance across government levels or between entities (e.g. a multi-national trade organization in coordination with the member states governments).

seems reasonable to select a particular *technological field* as the key unit of analysis for the *top down* approach (Schmidt et al., 2016). By contrast, the *bottom up* approach requires a narrower unit of analysis because the characteristics of technologies may differ significantly, even within a selected technology field, and hence strongly moderate the actual effect of policies on innovation (Arthur, 1989; Huenteler et al., 2016a, 2016b). The same holds true in case the focal technology can be applied to a range of different *use cases*. Hence, in the case of multi-purpose or general purpose technologies, concentrating on a *specific application* may additionally be necessary to limit the complexity of the analysis. In sum, when applying the *bottom up* approach, it seems reasonable to focus on a technology or a *sub-technology*, be explicit about the focal *use case*, and choose a specific *metric* along which the policy impact on innovation or technological change is measured (e.g. IP activities, economics, market growth).

Third, since this paper contrasts the two archetypical approaches of delineating a policy mix, the dependent variable, that means the overarching technology domain, must be identical in both cases. Accordingly, the *technology-application nexus* selected as a basis for the bottom up approach should be nested in the broader *technological field* used in the top down approach.

The case of energy storage policy in California

Based on the criteria outlined above, we choose to elaborate on the energy transition in the state of California. In particular, we select the *energy storage* domain as the focal *technological field* for the *top down* approach. This research case is well suited for our analysis, since California's policy landscape revolving around energy storage renders an application of the policy mix framework adequate and valuable. In recent years there has been an increased consensus among state legislators and regulators in California that the domain of energy storage, along with a number of other clean technologies such as electric vehicles, is a key building block of California's energy transition. This is due to the fact that the state's GHG reduction and renewable energy procurement strategies introduced in the mid-2000s have spurred the deployment of renewable generation capacity. Since energy storage provides one possible answer to the question of how incumbent electricity infrastructures may accommodate high penetrations of intermittent renewable resources – which becomes an increasingly pressing issue in California – innovation in this technological domain has gained strategic importance for policymakers. This shift is reflected in an emerging storage-specific policy agenda with strategic objectives (such as procurement goals) that are set by the Governor or the Legislator (Assembly and Senate). To achieve these goals four state-level entities, namely the California Public Utilities Commission (CPUC), the California Energy Commission (CEC), the California Independent System Operator (CAISO), and the California Air Resources Board (CARB) (details cf. Figure A.9), are jointly responsible for the design, implementation, and administration of these policy instruments. Since the energy storage domain comprises numerous technologies with distinct characteristics that may address a wide range of different applications in the energy system, devising an appropriate instrument mix is a challenging task. To do so, policymakers in California make use of different types of policy instruments and designs. In addition, the elements of this instrument mix also interact both with one another, and with other instruments across policy domains. Since the electricity sector is characterized by great technological complexity, and security of supply is of high importance, changes to the underlying infrastructure are often seen with skepticism, which imposes boundary conditions to the pace at which innovations gain traction. This is why governing the energy transition in the domain of energy storage is such a challenging task since it involves numerous trade-offs when it comes to the competition both between novel but uncertain, and established technologies, and between numerous emerging technologies. This situation renders coordination among the individual policy entities a non-trivial but highly important task, which is why certain elements of California's energy storage policy mix are developed by inter-agency initiatives. The fact that there are currently more than 300 open regulatory dockets on the topic of "energy storage" in California (AEE, 2016) reveals that many elements of California's energy storage policy mix are currently in flux. As a result, there is currently no database or report that offers a comprehensive (e.g. including different policy types), and comprehensible overview of policies relevant for the energy storage domain, much less so when it comes to the interaction or interdependencies between policies. Moreover, for the existing databases, we lack a clear terminology in order to unambiguously filter the entries relevant to energy storage. In sum, its multi-goal, multi-level, multi-instrument, and multi-entity features render California's energy storage policy mix an ideal case to explore different ways of operationalizing a policy mix and inductively derive valuable implications for theory and practice.

As the starting point for the *bottom up* approach, we select a case that is nested in the former technological field of energy storage, and that entails a specific decision about the focal *sub-technologies*, the *use case*, and the *metric* along which the policy effect is measured. In particular, we concentrate on *the economics* of *three specific storage technologies* for *residential PV self-consumption*[7], namely *lithium-ion battery storage*, *air-sourced heat pump*, and *immersion heater*. These three technologies are chosen since each of them addresses the three overarching objectives behind California's energy transition (GHG emission reduction, renewable integration, and technological innovation) to a different extend (cf. Table 1). This allows us to illustrate the challenges policymakers face when governing policy mixes that affect the competition between those technologies, since they ultimately need to trade off various policy goals against each other. The use case of *PV self-consumption increase* has been chosen since it is of increasing importance for California's energy transition (as outlined above), in particular for the emerging role of customer-sited renewables as one of the most disruptive trends for the incumbent electricity sector. Furthermore, we decided to use the *net present value (NPV)* as a common proxy for the *economics* of the three technologies applied in the selected use case, since it represent one of the key drivers

[7] This case has been selected due to its increasing relevance for the Californian energy transition. In particular, the rapidly increasing penetration of distributed solar PV systems leads to significant challenges for the operation and financing of the public electricity system. Distributed energy storage (DES) systems provide a promising solution to accommodate high shares of customer-sited renewable energy installations, and hence may become an enabling technology for the energy transition.

behind technological diffusion (and thus policy goal achievement), and it allows us to estimate the effect of a wide range of different policy instruments.

Table 1: Characteristics of the three storage technologies used as basis for the bottom up approach (full list of assumptions provided in Appendix)

		Policy goals				
		GHG emission reduction[1]	Renewable integration[2]			Innovation potential[3]
Case	Battery storage (BS)	31%	59%[a]	0% [b]	-15% [c]	High
Case	Air-sourced heat pump (HP)	48%	35%	0%	7%	Medium
Case	Immersion heater (IH)	29%	72%	16%	-4%	Low

[1,2] All values based on comparison between single-family household with “solar-plus-storage” system with identical building equipped with “stand-alone solar PV” system (details provided in Figure A.10–Figure A.12); 1 Relative CO_2 emission reduction; [2a] Relative increase of self-consumption rate; [2b] Relative decrease in annual maximum of PV system power output to the grid (feed-in); [2c] Relative decrease in annual maximum of PV system power output gradient (previous hour vs current hour) to the grid [3] Regarded as inversely proportional to technological maturity; assessment based on (Nykvist and Nilsson, 2015) for BS, (Kiss et al., 2012) for HP, and (Fuhrs, 2015) as well as desk research for IH

3 Methodology and Data

3.1 Overview of the empirical strategy

Given the aim of this paper to explore different approaches to delineate a policy mix, we conduct a qualitative case study of the aforementioned setting as it allows us to gain an in-depth understanding and inductively build theory on the core phenomenon (Eisenhardt and Graebner, 2007; Flick, 2009; Yin, 2009). To do so, we apply a three step strategy outlined in Figure 2. In a first step, we apply the top down and the bottom up approach individually (details provided below). Second, we contrast the outcome of the two approaches focusing our comparison on the differences between the underlying instrument mixes. To cross-check and enrich our preliminary findings we discuss them with experts on energy storage policy and innovation in California. Third, to illustrate how the narrow focus of the bottom up approach can be used to quantify the combined effect (both intended and unintended) of a policy mixes cutting across different policy fields, we conduct a techno-economic analysis of three deliberately selected policy instruments identified by the bottom up approach.

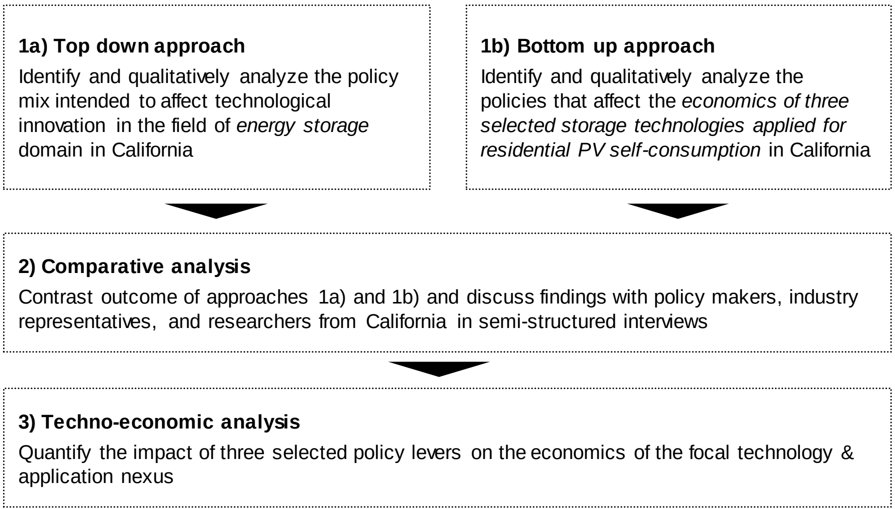

Figure 2: Overview of empirical strategy

3.2 Step 1a – Data collection via the "top down" approach

As outlined in Chapter 2.3, we follow the top down approach to delineate the key elements of the policy mix that pursues the *strategic intent* to *foster technological innovation in the field of energy storage* (cf. Figure 3). In doing so, it may be helpful to put oneself in the shoes of the policymakers responsible for governing the policy mix. However, the outcome of the top down approach, i.e. the scope of a given policy mix analysis, will always entail limitations and simplifications when it comes to depicting the real-world phenomenon (Flanagan and Uyarra, 2016). Hence, an application of the top down approach should not be confused with the analytical scope and capabilities of decision-makers involved in shaping real-world policy mixes.

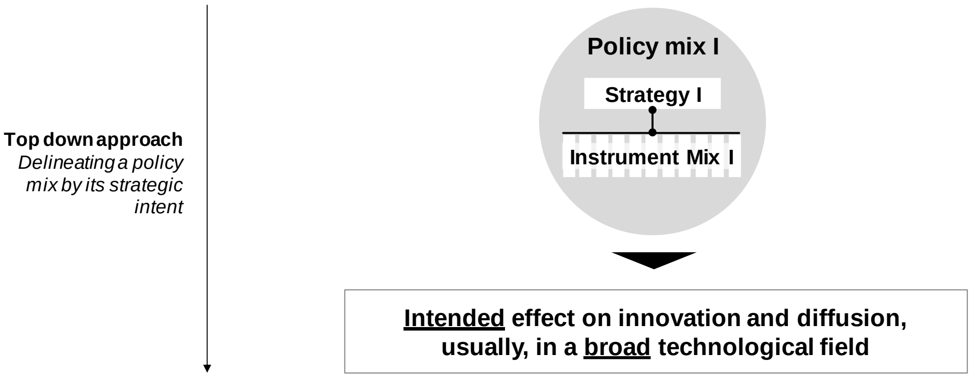

Figure 3: Research framework - the top down approach to delineate a policy mix
Based on Rogge and Reichardt (2016)

The analyses conducted by Shmidt et al. (2012) and Carl et al. (2012) on California's renewable energy instrument mix[8] serve as a starting point to understand how the state of California has governed its energy transition in the past. This includes gaining an overview of the central governing entities (their history, their mission, their organizational structure) and the relationships among them (vertical and horizontal coordination, individual and joint initiatives). The definition that any policy mix is embraced by a focal strategy[9] (Rogge and Reichardt, 2016) builds on the implicit assumption that a focal decision making authority has previously agreed on this strategy. This is why, for the top down approach, we deliberately focus on a single jurisdiction and governance level, namely the state level, and hence abstract from additional policy elements that are governed on the federal, or on the municipal level.

Furthermore, to be able to clearly differentiate the elements of the policy strategy from the policies contained in the instrument mix, we use the distinction between the California's Governor's Office and the Legislator (Assembly, Senate) on the one hand, and the four state-level agencies (CPUC, CEC, CAISO, CARB) on the other hand. While the former are assumed to govern the strategic level of the state's energy storage policy mix, the latter are assumed[10] to be responsible for the administration of the energy storage instrument mix.

[8] The authors coined the terms "renewable jungle", and "regulatory maze" to express the complexity and effort involved when it comes to gaining an understanding of how California's energy transition is governed.
[9] The policy mix strategy is composed of the strategic objectives or principal plans that reflect the intended effect(s) of a policy mix.
[10] This assumption was later cross-checked and confirmed as part of our expert interviews.

To identify the policy elements contained in both groups, in a subsequent step, we manually collected a comprehensive database of policy strategies and instruments in effect in the year 2016, which contained its commonly used acronym, its type, a brief description about its mechanism, the entity or entities responsible for its governance, and the year it came into effect for the energy storage domain (cf. Table A.4). This overview was assembled using publicly available data retrieved from the websites of California's government agencies (e.g. original text of bills and dockets), as well as the corresponding publications provided by these entities (e.g. annual reports). This data collection was complemented by additional information gathered from two policy databases[11], reports by industry associations and research institutes, press articles, stakeholder workshops, and webinars.

3.3 Step 1b – Data collection via the "bottom up" approach

As outlined in Chapter 2.3, we follow the bottom up approach to delineate the key elements of the policy mix that affects *the economics of three particular energy storage technologies used to increase the share of self-consumption of a residential solar PV installation* (cf. Figure 4). To do so, we adopt the perspective of the stakeholders who drive the underlying technological innovation system, in this case, the corresponding storage system vendors who attempt to derive an understanding about how the going policy mix affects the focal solar-plus-storage investment. Those actors are usually closest to the technology and its drivers in the sense that they know best about their current characteristics (lifecycle stage, cost, markets, customers) and hence are well aware of the intended and unintended effects of policies from various policy fields, levels or mixes. Once again, this does not imply that other stakeholders such as policymakers are not able to conduct the same analysis. In other words, an application of the top down approach should not be confused with the analytical scope and capabilities of decision-makers shaping or affected by a real-world policy mixes.

The analyses conducted by Darghouth et al. (2011), Hoppmann et al. (2014b), Luthander et al. (2015), and Sivaraman and Moore (2012) provide a comprehensive overview of the factors driving the economics of a residential solar-plus-storage investment California. The initial overview is then filtered according to the subset of antecedents that can be regarded[12] as policy instruments. In a subsequent step, we categorize these instruments according to their governance level (federal, state, local) and collect and manually review a comprehensive set of archival data in order to identify the responsible governing entities and corresponding strategies behind each of the instruments. Analogously to the top down approach we gather the corresponding type, mechanism and implementation data for each element of the mix, using a similarly wide range of data sources that are manually analyzed and categorized.

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[11] "Database of state initiatives for renewable energy" (SOURCE), "AEE Powersuite" (AEE, 2016)

[12] We stress this aspect since certain factors, such as electricity retail rates, should only be classified as policy instruments in case they are set by policymakers or the regulator, not in case they emerge freely out of a competitive retail market.

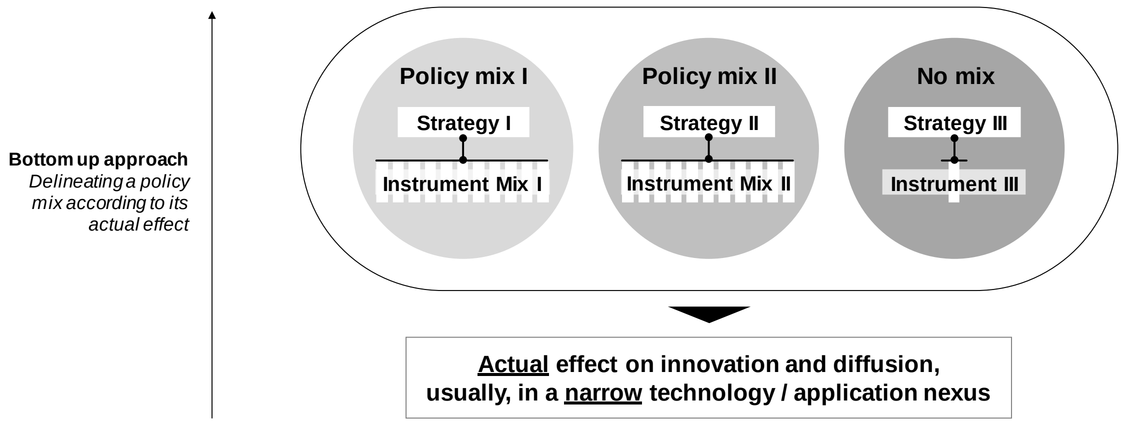

Figure 4: Research framework - the bottom up approach to delineate a policy mix; based on (Murphy et al., 2012; Nauwelaers et al., 2009)

3.4 Step 2 – Comparative analysis

Based on the previous step, we compare the outcome of the two approaches to delineate a policy mix. To validate our findings and gain further insights beyond the archival data dossiers, we discuss the similarities and the differences in 24 semi-structured interviews with experts on the energy transition in the United States and California, including policy makers and analysts, industry experts, and members of leading academic institutions (cf. Table 2). The interviews lasted between 15 and 75 minutes and were conducted over the phone or in person.

For about half of the discussions we arranged dedicated interview sessions, while the other half was conducted during breakout sessions in four academic[13] and two practitioner conferences[14]. In order to provide the basis for an open conversation, we granted all of the interviewees anonymity.

[13] Power Conference at Haas, Berkeley (2016); Silicon Valley Energy Summit (2016); Utilities Workshop at Stanford Business School (2016); Department of Energy Workshop at Stanford (2016)

[14] Energy Storage Europe (2015); California's Distributed Energy Future (2016)

Table 2: Overview of expert sample

Category	Person	Description
Policymaker / regulator / advisor	A	CPUC, Commissioner
	B	CPUC, Commissioner
	C	CPUC, Staff member
	D	FERC, Department head
	E	CEC, Department head
	F	NARUC, Board Member
	G	Minnesota PUC, Commissioner
	H	PSC Washington DC, Department Head
Energy storage industry / association	A	Storage system vendor 1, Head of Energy Policy
	B	Storage system vendor 2, Head of Energy Policy
	C	Storage system vendor 3, Head of Technology
	D	Storage system vendor 4, Head of Business Development
	E	Storage system vendor 4, Head of Sales
	F	Electric utility 1, Head of Customer Services
	G	Electric utility 1, Head of Innovation Department
	H	Industry association 1, Head of Energy Policy
	I	Industry association 2, Head of Energy Policy
Academia / research institutions	A	Private University 1, School 1, Senior Researcher
	B	Private University 1, School 2, Senior Researcher
	C	Private University 1, School 2, Senior Researcher
	D	Private University 1, School 3, Senior Researcher
	E	Private University 1, School 4, Senior Researcher
	F	Public Policy think tank 1, Senior Researcher
	G	Private Research Institute, Senior Researcher
	N = 24	

3.5 Step 3 – Techno-economic analysis

Since the bottom up approach builds on a narrow definition of the focal impact domain, it allows us to quantify the effect of the policy mix, highlighting a potential avenue for to future policy mix analyses. To do so, we build on a techno-economic simulation toolset that was developed in previous work (Lang et al., 2016, 2015, 2013) and significantly extended for the purposes of the analysis at hand. In particular, we adopt the perspective of a residential homeowner who analyzes the net present value (NPV) of the three energy storage technologies to be used for residential PV self-consumption increase (cf. Chapter 2.3). For each of the investment cases, we calculate the sensitivity to three policy instruments that have been identified using the bottom up approach (cf. Figure A.14–Figure A.16). The policies were selected since they illustrate the challenges that policy makers face when governing policy mixes. In particular, even though the three policies are all governed both from the same governance level (the state of California), and by the same governing agency (the CPUC), they strongly differ with regards to their impact on the economics of the three focal storage technologies.

4 Results

4.1 A top down view on California's energy storage policy mix

The result of the *top down* approach, namely the elements of California's energy storage policy mix, is provided in Figure 5. Following the terminology of Rogge and Reichardt (2016), we distinguish between the *policy strategy,* comprising 14 elements, and the *instrument mix,* comprising 27 elements. As indicated in section 2.3, California's *energy storage* strategy is a derivative of its overarching *climate change* and *energy transition* strategy, which was initiated by the State Legislator as a response to an energy crisis in the early 2000s and led to the development of an "Energy Action Plan" (EAP) that was introduced in 2003 (cf. Fig. 5-1). The EAP involved a "Loading Order" which stated the state's energy policy and investment priorities as 1) energy efficiency and demand response, 2) renewable and distributed generation, and 3) clean fossil-fueled sources and infrastructure improvements. This strategy was later complemented by specific milestones for greenhouse gas (GHG) reduction, energy efficiency, and renewable procurement that were regularly extrapolated and intensified, most recently through Senate Bill 350 in 2015 (cf. Fig. 5-4).

The energy storage domain started to gain the Legislator's attention around 2010, when Assembly Bill 2514 (cf. Fig. 5-3) directed the CPUC to "open a proceeding to determine appropriate targets […] for each lead-serving entity to procure viable and cost-effective energy storage systems" (AB2514, 2010, p. 2). The rationale behind the promotion of energy storage was the gradual replacement of high-polluting, rarely operating power plants dedicated to peak load hours, and the provision of alternatives to building new ones. In addition, the procurement program can be regarded as a proactive step in the anticipation of an increased demand for fast-ramping capacity[15], based on projections of a significant increase of intermittent, renewable generation[16], in particular from solar PV. The aforementioned strategic objectives and principal plans set in motion a series of activities by California's four major agencies responsible for governing the electricity sector, namely CAISO, CARB, CEC, and CPUC, which led to the emergence of the *instrument mix* that is depicted in the lower part of Figure 5.

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[15] This scenario, i.e. an increasing trough in California's aggregated load-curve around mid-day, is being discussed under the term "duck curve" (Blunden, 2015; CAISO, 2016).

[16] This aspect was also addressed by AB33 in 2016, which stressed the ability of "long duration bulk energy storage resources […] to meet [the] electrical grid's need for rapid ramping capability and the capacity to utilize overgeneration from renewable energy resources", and asked the CPUC and CEC to assess the technical potential and carry out cost-benefit analyses for a wide range of storage technologies (AB33, 2016, p. 1) (cf. Fig. 5-5).

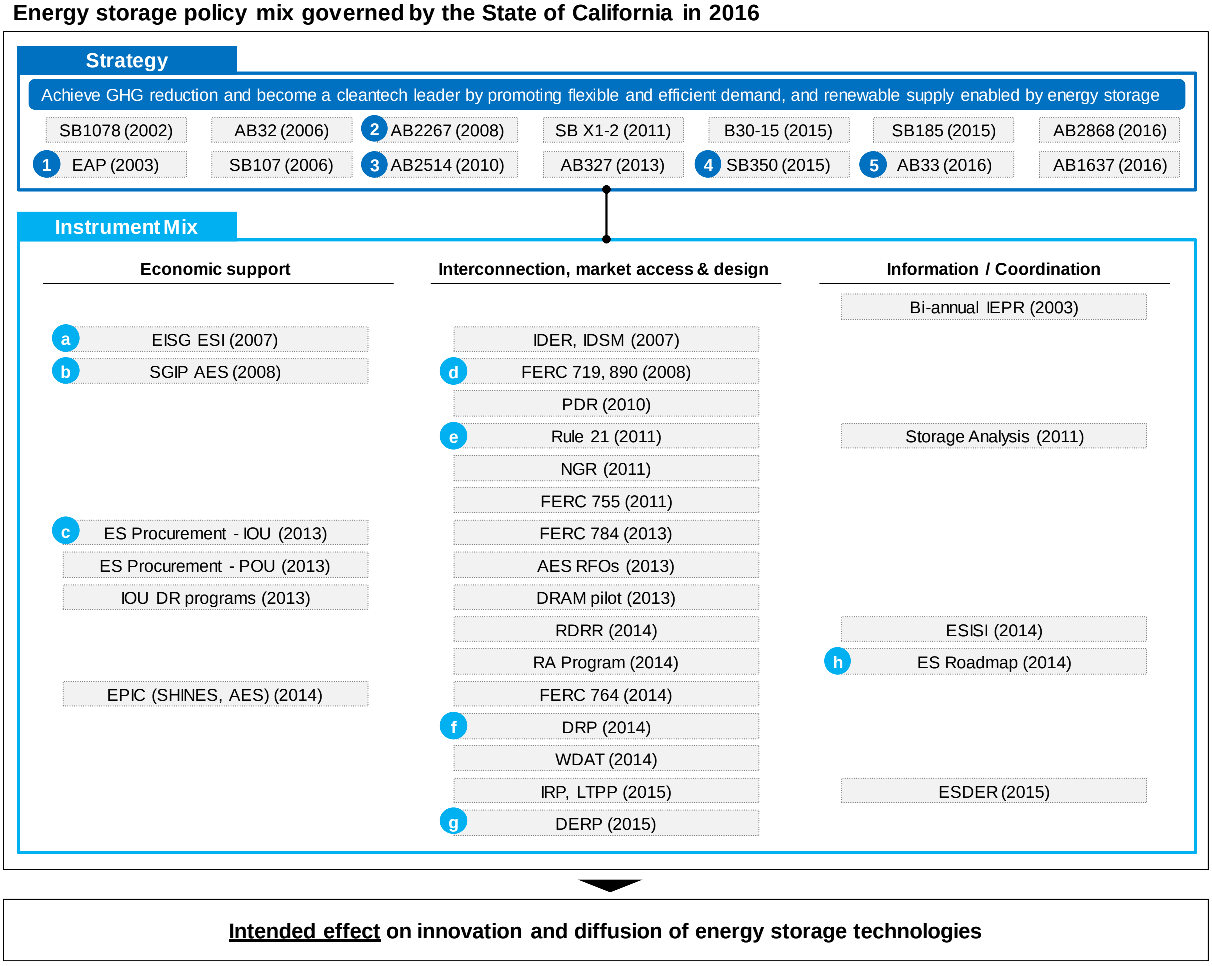

Figure 5: Outcome of the top down approach – California's policy mix geared towards energy storage innovation in 2016; the numbers and letters indicate policy elements that are detailed in the text; all abbreviations and features of the corresponding policy elements are scrutinized in Table A.4

We find that the mix comprises three types of policy instruments, namely *economic support*, *regulation*, and *information* (cf. three columns[17] in Figure 5), as classified[18] by Vedung et al. (1998, p. 30, Figure 1.5). This indicates that California's policymakers pursue a multi-lateral approach when it comes to establishing energy storage systems as a novel technology domain in the electricity system. For example, there are multiple programs that offer support for research, development, and

[17] The policy elements are sorted along the vertical axis according to their year of coming into effect. The fact that most of the instruments have been implemented over the last five years underscores the dynamics behind and importance of California's emerging energy storage policy mix.

[18] Building on the observation that "the government may either force us, pay us or have us pay, or persuade us", the original article introduced the distinction between *carrots* (economic levers), *sticks* (regulatory levers), and *sermons* (provision of targeted information).

demonstration (RD&D) in the domain of energy storage, such as the "Energy Innovators Small Grant" (EISG) that entails a dedicated subject area for "Energy Systems Integration" (cf. Fig. 5-a). When it comes to bridging the gap between technological innovation and market diffusion, the state e.g. provides a Self-Generation Incentive Program (SGIP) that was amended in 2008 to include upfront grants for "Advanced Energy Storage" (AES) systems (cf. Fig. 5-b). In the same year, Assembly Bill 2267 directed the SGIP program administrators to increase this amount by 20% in case the eligible technology was sourced from a Californian supplier (cf. Fig. 5-2). This indicates that industry policy, i.e. the creation of a lead market for energy storage, is part of the strategic priorities of State Legislator, and hence an element of California's energy storage policy mix. To comply with AB2514 (outlined in the previous section), in 2013 California's three state-regulated, investor-owned utilities (IOUs) revealed their plans to procure 1,325 MW of grid-connected energy storage system through competitive solicitations until 2020 (cf. Fig. 5-c), a figure that the State Legislator expanded by an additional 500MW in 2016 (cf. AB2868).

In addition to these *technology push* and *demand pull* instruments (Nemet, 2009; Peters et al., 2012; Taylor, 2008), the state of California has also launched a series of activities to amend the state's regulatory complex in order to provide fair rules for the interconnection and market participation of energy storage devices. Examples include orders 719 and 890 by the Federal Energy Regulatory Commission (FERC) in 2008 (cf. Fig. 5-d), which requested the Independent System Operators (ISOs), such as CAISO, not to discriminate against new resources such as energy storage systems when it comes to their participation in regional ancillary services markets. This passage was later extended to account for the distinct characteristics that e.g. battery storage systems may provide to the electricity system such as fast-responding and highly accurate frequency regulation (cf. FERC755, 784). In addition, the CPUC has launched a number of proceedings to e.g. improve the existing "Electric Tariff Rule 21" which included adapting the rules and regulations for distribution level interconnection in order to account for the role of electric storage resources (cf. Fig. 5-e). Since much of the information on California's electricity system has been in the hands of the three incumbent IOUs, in 2014 the CPUC mandated them to hand in "Distributed Resource Plans" (DRPs) by mid-2015, a response to Assembly Bill 327 which had passed in the year before (cf. Fig. 5-f). The DRP rulemaking[19] can be seen as a prerequisite of turning California's distribution grid into a plug-and-play system e.g. for distributed energy storage facilities attached to customer-sited renewable energy systems (cf. below).

Last but not least, several reports have been launched in order to facilitate coordination among the different agencies and stakeholders driving California's energy transition. For instance, building on

[19] The DRP rulemaking (R.14-08-013) requires the utilities to disclose bi-annually how they intend to integrate distributed energy resources (DER) into their grid planning and operations, by conducting an "Integrated Capacity Analysis" and a "Locational Net Benefit Analysis", and providing public access to the underlying data.

the expertise and feedback of more than 400 interested parties, CAISO, CEC, and CPUC developed the "Energy Storage Roadmap" as an inter-agency guideline to clarify the milestones and priorities for the state's energy storage policy mix, and agree on particular individual and shared deliverables for each of the governing entities (cf. Fig. 5-h). In confluence with agency-specific information and stakeholder integration efforts such as CAISO's "Energy Storage Interconnection Stakeholder Initiative" (ESISI) or the CEC's bi-annual "Integrated Energy Policy Report" (IEPR), these activities complement the list instruments that combine to establish California's policy mix geared towards technological innovation in the domain of energy storage.

4.2 A bottom up view on the policy mix affecting the economics of energy storage for residential PV self-consumption in California

The result of the *bottom up* approach, namely the policy mix affecting the *economics of three specific residential solar-plus-storage investments* in California, is provided in Figure 6. Once again, we distinguish between the *policy strategy,* comprising 14 elements, and the *instrument mix,* comprising 11 elements. The most apparent contrast to the top down approach is that the bottom up policy mix comprises elements that are governed both by the state of California (cf. middle section of Figure 6), as well as federal and local authorities.

The reason is that two federal policy instruments, namely the "Residential Renewable Energy Tax Credit" (ITC-PV/BS), and the "Residential Energy Efficiency Tax Credit" (ITC-HP), affect the economics of two of our focal sub-technologies, namely battery storage systems, and heat pumps respectively (cf. Fig. 6-a). As federal investment tax credits, these two instruments are governed by the U.S. Internal Revenue Service (IRS). However, they should not be seen as part of the regular fiscal policy activity, but as a result of three overarching strategic policy frameworks introduced by the Legislator under the Bush and Obama administrations. These include the "Energy Policy Act" (EPACT) of 2005, the "Energy Improvement and Extension Act" (EIEA) of 2008, and the "American Recovery and Reinvestment Act" (ARRA) of 2009 (cf. Fig. 6-2)[20].

[20] While EPACT was introduced as part of the federal energy policy mix with the direct intent to support renewable energy technologies, the EIEA and ARRA frameworks should rather be seen as an immediate response to the global financial crisis with an indirect intent to foster innovation in the energy domain, e.g. through the foundation of the "Advanced Research Projects Agency – Energy" (ARPA-E) in 2009.

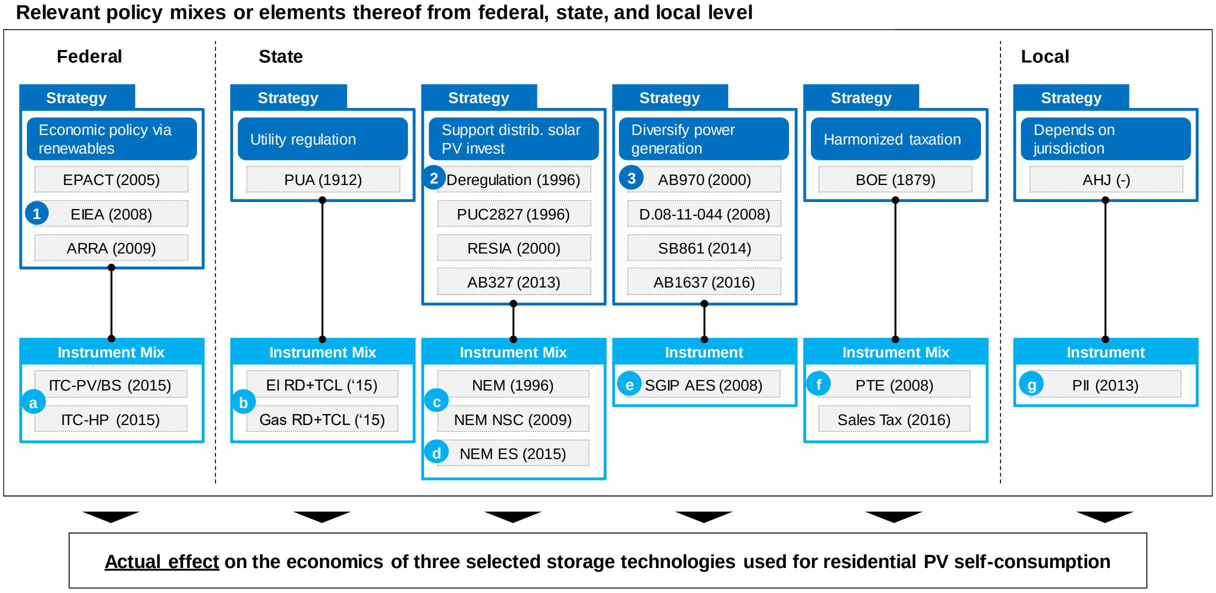

Figure 6: Outcome of the bottom up approach - Policy mix affecting the economics of residential solar-plus-storage in California, 2016; the numbers and letters indicate policy elements that are detailed in the text; all abbreviations and features of the corresponding policy elements are scrutinized in

Table A.5

In addition to the federal-level support schemes, there are multiple state-level policy instruments that have an effect on the economics of residential solar PV self-consumption. These can be clustered into four individual instrument mixes, whereby each of these mixes is governed by an individual strategy. The first group (cf. Fig. 6-b) comprises electricity and gas rates, as well as the corresponding taxes, charges, and levies associated with their consumption, since these determine the level of bill savings that can be expected from our solar-plus-storage investments. Electricity and gas rate design can be regarded as policies, since California's retail markets for the two commodities are regulated by the state[21]. The second group is comprised of the Net Energy Metering (NEM, cf. Fig. 6-c) scheme, which mandates utilities to provide bill credits to residential solar PV owners for excess electricity being fed into the public grid, a result of the temporary electricity sector deregulation in the late 1990s (cf. Fig. 6-2). Currently, the feed-in rate is currently set at the going electricity retail rate, which renders stand-alone solar PV systems attractive investments among many residential customer segments since

[21] In particular, every three years the CPUC approves "general rate cases" provided by the state-regulated "load-serving entities" to comply with its mission to provide a "safe, reliable utility service and infrastructure at reasonable rates".

the revenues considerably exceed[22] the levelized cost of electricity (LCOE) generated by these installations. This policy has been included in our analysis since it determines how economically attractive it is to use electricity onsite, rather than exporting it to the grid. Furthermore, the instrument relieves owners of PV and PV-plus-battery systems (cf. NEM ES, Fig. 6-d) that are eligible for the NEM program, from a number of administrative charges and grid interconnection fees. The third is an individual policy instrument, rather than an instrument mix, namely the "Self-Generation Incentive Program" (SGIP AES, cf. Fig. 6-e). It can be traced back to Assembly Bill 970 from 2000 which directed the CPUC to introduce load control and distributed generation activities, hence it can be regarded a means to implement one of the strategic objectives of California's energy transition, namely a diversification of power generation resources. However, as mentioned above, "advanced energy storage" (AES) only became eligible for the upfront support provided by SGIP in 2008 (cf. decision D.08-11-044), which was one out of many amendments that have characterized this policy instrument over time (for a complete overview cf. Figure A.13). We identified SGIP as an element in the bottom up policy mix, as the instrument significantly reduces the investment costs of battery systems, one of the technologies of our focal impact domain. Fourth, two state-level tax instruments exert opposing effects on the economics of residential solar-plus-storage in California. The Sales Tax, which is harmonized and administered by the Board of Equalization (BOE), increases the upfront costs of each of our investment cases by about 8%. The Property Tax Exclusion (PTE, cf. Fig. 6-f), which goes back to two Assembly Bills that led to the amendment of California's Revenue and Taxation Code Section 73, however, exempts[23] buildings with "active solar energy systems" (including storage devices) from increases in property tax.

Last but not least, similarly to the two federal-level policy instruments, the costs of "Permitting, Inspection and Interconnection" are highly location-specific and depend on more or less efficient procedures by the corresponding "Authority Having Jursidiction" (AHJ), such as a given municipality (cf. Fig. 6-g). Hence, it is impossible to assign a particular policy strategy to the former policy instrument which puts into question whether it makes sense to conceptualize it as part of a local level policy mix. As we have seen above, the bottom up approach proceeds by first identifying the instrument mixes affecting the focal impact domain, and uncovering the corresponding strategies for each of the mixes in a second step. The result may be regarded as a "blend" of different policy mixes, rather than a single, integrated policy mix that deliberately follows a given strategic intent.

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[22] However, receiving feed-in compensation comes with the limitation that owners must dimension their PV systems to their annual electricity demand, setting the net electricity bill to zero. Any electricity that is fed in in excees of this constraint, is still compensated, but at a level (cf. NEM NSC) considerably below the levelized cost of electricity. This renders "over-sizing" PV systems for grid production economically unattractive.

[23] Similar installations (regarded as "new constructions") normally trigger a reassessment of the corresponding property's market value. This usually entails future increases in property tax, which would drag down the returns of each of our focal investments.

4.3 Comparing the top down and the bottom up approach

As the previous results have shown, there is surprisingly little overlap between the two sets of policy elements collected using the *top down* approach as opposed to the *bottom up* approach, which holds true both for the strategies as well as for the underlying instruments. Figure 7 concentrates on the latter, and highlights that there is only one policy instrument which is identified by both approaches, namely the *SGIP* (cf. left-hand side of the figure). In other words, SGIP is the only policy instrument from California's *energy storage policy mix* that affects the economics of our one focal residential solar-plus-storage cases, by offering an upfront grant for battery systems. This, in turn, means that there are numerous policy levers outside the realm of the *energy storage policy mix* that impact the investment into batteries, heat pumps, and immersion heaters used as a complement to residential solar PV systems.

The case of *NEM* reveals that it may be important to capture these side-effects from other policy fields. In particular, even though the NEM scheme does not intend to affect the energy storage domain, and hence would not be considered part of the *top down* energy storage policy mix, it strongly affects the economics of distributed energy storage systems by implicitly offering the electricity grid as a free of charge storage alternative. The *SGIP vs NEM* case shows that the *bottom up* analysis may be useful to reveal and rule out potential inconsistencies between the effects of policies that do not fall under the same policy strategy, and hence, would not be regarded part of the same policy mix from a *top down* perspective.

The reason for the significant difference in the outcome of the two approaches to delineate a policy mix can be found in the different levels and units of analysis of the impact domain. In particular, the *top down* approach starts from the notion that the energy storage policy mix intends to affect innovation across the entire energy storage landscape as depicted on the right-hand side of Figure 7. As indicated by the matrix, several storage technologies (vertical axis) can be applied in multiple use cases (horizontal axis) (cf. Chapter 2.3). By contrast, the *bottom up* approach concentrates on a very small part of the energy storage landscape, namely three selected energy storage technologies applied for PV self-consumption increase, and focuses on a specific metric to measure the policy impact, namely the economics of the corresponding three installations.

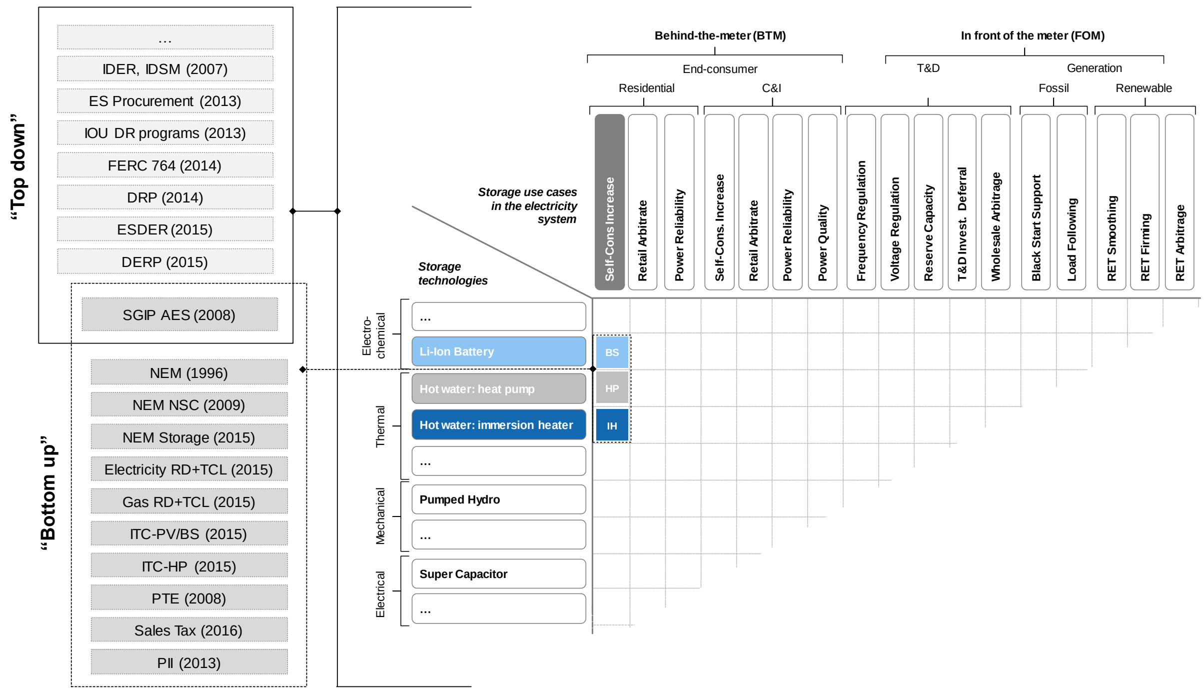

Figure 7: Comparison of top down and bottom up approach; left-hand side: Venn-diagram of instrument mixes identified by each approach; right-hand side: matrix of technologies and use cases in the domain of energy storage

4.4 Techno-economic analysis of three selected policy instruments identified using the bottom up approach

To illustrate how California's policy mix affects the additional net present value (△NPV) of investing into one out of the three focal storage technologies[24], we conduct a techno-economic analysis. As shown in Figure 8, we analyze the effect of three selected policy instruments identified by the bottom up approach, namely *SGIP* (vertical axis), the *level of feed-in remuneration* (x-axis in each of the 9 graphs; used as a proxy for *NEM*), and the *retail price for natural gas* (horizontal axis). We find that the three policy instrument significantly affect the economics of adding an energy storage device to a given residential solar PV installation. The fact that the NPV curves for the three investments cross each other, reveals that the different policy scenarios affect the competition between the focal storage technologies. To highlight this aspect, we indicated the changing "competitive order" in the upper right corner of each of the graphs, in case the investments turned out to be NPV positive. Under the

[24] Each of these investments are compared to a "baseline" case, in which a stand-alone PV system is installed (cf. Figure A.12).

moderate scenario (cf. Figure 8, graph 5), we find that the competition between the three storage technologies can be framed as a head-to-head race.

Scrutinizing the antecedents of the policy-induced shifts in the storage economics, we find that the battery storage (BS) system benefits from an increase in the level of upfront grants provided by *SGIP* (cf. Figure 8, rows 1 to 3), whereas the economics of the two power-to-heat conversion technologies remain unchanged. The opposite is true for an increase in *retail gas prices* (cf. Figure 8, columns 1 to 3). In this case, both the heat pump (HP) and the immersion heater (IH) investments benefit from an uptake in the potential savings on the natural gas bill, whereas the economics of the battery storage system remain identical. When it comes to the impact of an increase in *feed-in remuneration*, the economics of all three focal storage technologies suffer. The reason is that the higher the compensation paid for electricity being fed into the public grid, the lower the incentive to store the electricity onsite once all instantaneous power demand is met. This holds true independent of whether the electric energy is stored electrochemically in a battery to serve later electricity demand, or thermally in a hot water reservoir. The extreme right of the graphs illustrates the situation under the current *NEM* scheme, where electricity feed-in is compensated at the going retail electricity rate. Put into net present value terms, this virtual storage option yields US$ 7,200[25] worth of retail electricity savings over the lifetime of the investment. Hence, in this setting which represents the situation in California in 2016, only the heat pump remains a viable investment in case of high gas retail rates (cf. Figure 8, graphs 3, 6, and 9).

Each of the three focal policy instruments depicted above is part of an individual policy mix with a corresponding policy strategy, even though all of them are governed by one single entity, namely the CPUC. Our analysis stresses that policy makers should be aware of considerable (tolerable or critical) side-effects, some of which could be uncovered and further scrutinized by applying the bottom up approach to a range of relevant technologies and applications being impacted by policies. The reason is that the combined effect of these policies may lead to a deviation from the overarching strategic objectives of California's energy transition (cf. Chapter 2.3). Our analysis of how policies affect the economics and hence the competition between three particular energy storage technologies reveals the difficulty but also the importance of making informed policy decisions for which systematic policy mix analyses provide a valuable tool.

[25] Calculated for a solar PV stand-alone system, assuming a discount rate of 3%. For real-world distributed energy storage (DES) to be competitive against this value proposition, the installations would need to receive support in an order of magnitude that would cover both CAPEX and OPEX and even add a surplus to compensate for inefficiencies in the storage process and for the limitations in storage capacity.

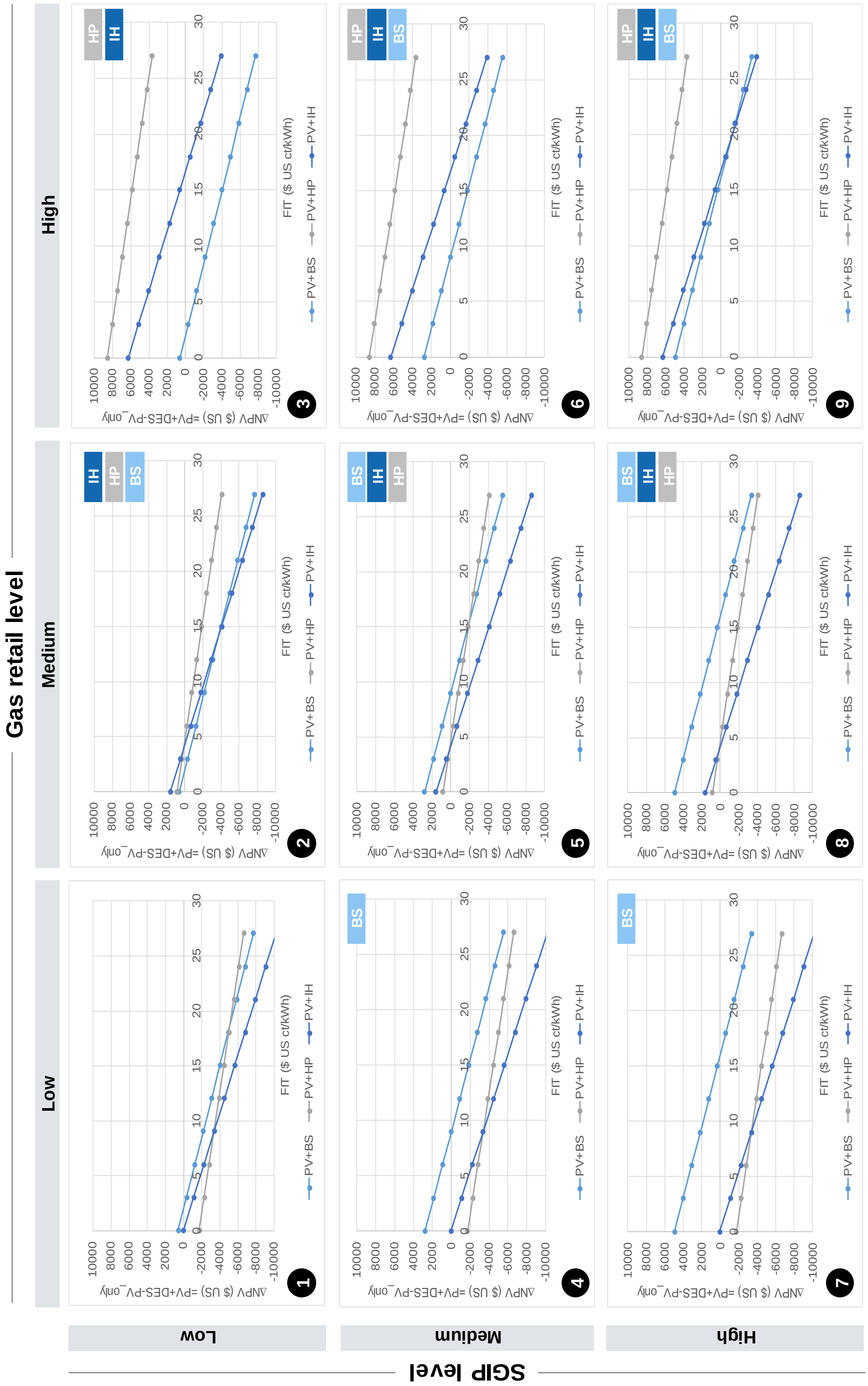

Figure 8: Analyzing the combined effect of three policies on the economics of three energy storage technologies used for PV self-consumption increase

5 Discussion

5.1 Implications for Theory and Practice

To support the development of policy portfolios that drive sustainability transitions, this study has introduced a dichotomy between two archetypical approaches to delineate a policy mix – *top down* vs *bottom up* – which may provide the basis for a systematic and consistent study of the policy mix phenomenon. In addition, we have explored how each of the two approaches affects the scope and subsequent analysis of a policy mix.

Elaborating on the case of energy storage in California, we found that while the two approaches deliver different sets of policy elements, it does not seem reasonable a priori to favor one approach over the other. Instead, the suitability of the approaches for policy analyses depends on the specific research design. To provide a guideline for future policy mix analyses, in the following we outline and evaluate the two approaches. The upper part of Table 3 summarizes the conceptual and methodological basis of the two approaches, which is detailed in Chapters 2 to 0, while the lower part provides an assessment that builds on the results of our analysis, and the observations gained in the analytical process.

Table 3: A guideline for delineating policy mixes: the choice between the top down and the bottom up approach

Category	Top down	Bottom up
Delineate mix by	Overarching strategic intent	Actual effect on a focal impact domain
Perspective	Policy maker shaping the policy mix	Actors driving technological innovation and diffusion
Policy scope	One jurisdiction	Multiple governing levels
Technology scope	Technological field	Technology, sub-technology
Advantages	▪ Comprehensive view on change in a broad technological field ▪ Reveals vertical and horizontal coordination challenges *within a given policy mix*	▪ Helps identify intended and unintended policy effects and interactions between instruments ▪ Reveals vertical and horizontal coordination challenges *across policy fields*
Disadvantages	▪ Hard to apply in the initial phase of emerging policy mixes ▪ Prone to "green field" [1] assumption	▪ Focuses on policy impact on a narrow technology-application nexus ▪ Choice of impact metric may affect the scope of policies [2]

[1] Tendency to create new support scheme for niche technologies instead of identifying and removing existing barriers associated to the regime. [2] For example, estimating the impact of regulatory and informatory instruments is harder than for economic measures.

In general, we find that both approaches entail specific advantages and disadvantages that should be weighed against each other when it comes to deciding which approach to pursue. While in theory it may be possible to combine[26] both approaches, we assume that this would come at the costs of comprehensibility, which should be regarded an important criterion for valuable policy mix analyses.

Instead, we suggest to conduct the top down approach when the focus lies on the analysis and the improvement of the governing structure to further develop a given policy mix. Elaborating on the organizational configuration between and within the associated governing entities can be regarded a prerequisite to understand a) where policy elements and competences are located, and where policy processes occur, b) whether and how well the former are coordinated, and c) which institutions need to be changed when it comes to the further development of a focal policy mix. For example, the fact that the state of California has (not yet) put in place a dedicated "energy transition" agency, but rather relies on the distributed capabilities of its existing institutions[27], has strong implications for the internal dynamics of its "energy storage policy mix" (Carl et al., 2012; Grueneich and Carl, 2012). Hence, we argue that in order to understand the interplay between the elements of a policy mix, one has to be explicit about the interplay between the governing actors. Similar to a large corporation, the organizational structure, and institutional history behind the policy mix may moderate whether and how coordination takes place.

By contrast, the bottom up approach is better suited to identify barriers and side-effects across different policy fields and governance levels which leads to the inclusion of a broader scope of relevant policy entities both within a given governance level (e.g. a state), and across levels of governance (cf. federal-state-local). Thus, it may reveal inconsistencies between unrelated policy domains that may be overlooked when conducting the top down approach. In this regard, it would be of great value if providers of existing energy policy databases complemented their data repositories with a more consistent and comprehensible terminology to search and filter for storage-specific entries in a bottom up manner. However, given the large number of combinations between storage technologies and possible use cases, this task appears to be much more challenging compared to the domain of renewable energy technologies (Battke and Schmidt, 2015; Malhotra et al., 2016; Stephan et al., 2016). In addition, the narrow focus on a particular technology, application, and impact metric, allows analysts to assess the effect of the focal set of policies using quantitative approaches. As our analysis has shown, this ability may be highly valuable to gain further insights into the combined effect of policies on a number of proxies for technological change (patenting activities, economic viability,

[26] For example, the bottom up analysis could be rendered for all sub-technologies in a given technological field. Similarly, the top down approach could be complemented by simulating a wide range of potential effects of a given policy mix and comparing it to the "intended impact" along different goals

[27] CEC: R&D and energy policy coordination; CPUC: IOU regulation / distribution grid and retail market; CAISO: nondiscrimination of wholesale market participants; transmission grid; CARB: regulates emissions of carbon dioxide, criteria air pollutants, and particulate matter (cf. Figure A.9)

market diffusion), and to estimate to how well the instrument mix contributes to the achievement of the overarching strategic goals.

In sum, it appears that the top down and the bottom up approach entail many complementarities, with the strengths of each being the weaknesses of the other. For instance, while the top down approach is well suited to comprehensively capture the elements of a policy mix that intend to shape innovation in a given technological field, it may fall short of revealing the unintended impacts from related policy fields. The opposite is true for the bottom up approach, which focuses on a specific segment of a larger technological domain, but captures both the intended and the unintended policy effects across policy fields. A closer look at California's energy transition shows that policy makers leverage these complementarities by combining their own top down perspective, with the multi-faceted bottom up expertise from industry stakeholders. The reason is that the industry, being the closest to the technologies, their potential applications, and their corresponding business models, is usually best equipped to estimate the potential effect of policy instruments and their particular design. As our analysis reveals, the agencies responsible for governing California's electricity sector have already implemented many of such systematic, long-term stakeholder engagement processes, the inputs of which have started to shape the state's energy storage policy mix (cf. SGIP, ESISI, ESDER, Figure 5).

However, the inclusion of stakeholders in the policy making process may entail a number of challenges. For example, the moderators need to ensure that multiple perspectives can be brought to the table, and avoid incumbent stakeholders from dominating the discussion. This may be especially difficult in the formation phase of a technology, when no clear associations of niche players exist that could voice the opinions of the emerging industry. To counter the influence of incumbent actors pursuing "nonmarket strategies" (Bonardi et al., 2006), policymakers should therefore consult independent experts and research institutes that could conduct multiple bottom up analyses to assess how the existing policy landscape affects a sample of emerging technologies.

Given their central role for both the top down and the bottom up approach, we suggest that "actors" should be incorporated more explicitly in the policy mix framework, rather than treating them as a mere dimension such as time or geography. In particular, policy makers and the organizational structure of the key governing agencies could be framed as a "missing link" between policy processes and elements (strategies, instruments). In addition, explicitly incorporating the stakeholders who drive innovation in the focal technological domain is of key importance when it comes to gaining an in-depth understanding of the bidirectional link between policy mixes and sustainability transitions.

5.2 Limitations and Further Research

Our study has limitations, some of which can be regarded avenues for future work. First, since our analysis is based on California's electricity sector, it remains open to which extend our findings are generalizable to other jurisdictions. Expert interviews with representatives from regulatory agencies across the United States suggested that many of our results could be transferred to their local context.

The same holds true for the discussions we had with firms which are active in multiple regions. Furthermore, our focus on the electricity industry may question the degree to which our findings can be transferred to other industries, and sustainability transitions therein. The electricity sector is a highly regulated environment, e.g. due to the fact that the grid is seen as a “natural monopoly”, with a traditionally strong role for legislators and regulators. This may increase the number of co-existing policy instruments, and the complexity arising from their coordination, which may be less pronounced in other sectors. In addition, it could be incumbent firms in the electricity sector (most importantly electric utilities and grid operators) play a more dominant role than established firms in other industries. This, in turn, may affect the degree of resistance against changing market conditions that policy makers need to overcome, and the level of stakeholder engagement that is necessary to address potential information asymmetries between government entities and the industry. Future research should therefore apply the top down and bottom up approach across jurisdictions and industries, to identify potential contingencies.

Second, additional research is needed to assess to which degree the two approaches can be applied at different stages of the lifecycle of a given policy mix. Currently, there is an implicit assumption that the mix of policy instruments emerges as a result of a given overarching policy strategy. As our top down analysis of California’s energy storage policy mix shows, this is not necessarily the case. Several instruments existed before innovation in the energy storage domain became a dedicated strategic objective. This is in line with previous research which stresses that emerging policy mixes usually blend in with existing policies, such as in the case of the Dutch energy transition which “was expected to rely partly on existing policy instruments (e.g. R&D policy, ETS) and partly upon the development of new ones, with the ambition to create a consistent instrument mix” supporting the overarching goal of a “long-term structural change in the energy system toward sustainability” (Kern and Howlett, 2009, p. 401). Therefore, further research should elaborate on suitable indicators to clarify how different stages of policy mixes can be distinguished from one another, and what this distinction implies for the analysis of potentially transient characteristics based on the policy mix framework. Furthermore, in some cases there was ambiguity with regards to the assignment of a given instrument to an overarching strategic intent. In other words, depending on the argumentation, a given instrument could be assigned to multiple strategies. Hence, further research should clarify whether policy mixes can actually be conceptualized as mutually exclusive, and, if not, how the aspect of overlapping can be included in the policy mix framework.

Third, further research could build on our techno-economic analysis of the bottom up approach, and e.g. render a sensitivity analysis to estimate the individual, and the combined impact of the full range of policy instruments identified by the bottom up approach. This could provide further insights into the antecedents of policy mix complexity, help uncover further potential inconsistencies, and ultimately improve the coordination of policy instruments within and across policy fields.

6 Conclusion

This study addressed the research question of how two archetypical approaches to delineate a policy mix – *top down* vs *bottom up* – affect its scope and subsequent analysis. Studying the case of energy storage policy in California, we show that each approach leads to significantly different sets of policy elements (strategies and instruments). Since the two approaches lend themselves to different types of policy mix analyses, we suggest to frame them as complements, rather than alternatives. In particular, the top down approach is well suited to shed light on internal dynamics and the governance structure behind a focal policy mix with a given strategic intent. By contrast, the bottom up approach is preferable when it comes to analyzing the intended and unintended interactions between policy elements across different domains. Our study should be regarded a first step towards a consistent guideline for the initial step of every policy mix analysis, namely defining the boundary of the core phenomenon. Hence, we hope that our work inspires future research that further develops the top down vs bottom up dichotomy.

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Appendix

Entities responsible for shaping Policy Strategy

Governor	Assembly	Senate

Entities responsible for shaping Instrument Mix (Instrument Design, Implementation, and Administration)

California Public Utilities Commission (CPUC)	California Independent System Operator (CAISO)	California Energy Commission (CEC)	California Air Resources Board (CARB)
Established 1911	**Established** 1997	**Established** 1973	**Established** 1967
Mission “Provision of *safe, reliable utility service and infrastructure at reasonable rates*, with a commitment to environmental enhancement and a healthy California economy”	**Mission** “Provides open and non-discriminatory *access to the bulk of the state’s wholesale transmission grid*, supported by a competitive *energy market* and comprehensive *infrastructure planning* effort”	**Mission** “Reducing energy *costs and environmental impacts* of energy use – such as greenhouse gas emissions – while ensuring a *safe, resilient, and reliable supply* of energy.”	**Mission** “Promote and protect public health, welfare and ecological resources through the *effective and efficient reduction of air pollutants* while recognizing and considering the effects on the economy of the state.”
Governance “Five Commissioners, appointed by the Governor, approved by the Senate”	**Governance** “Governed by a 5 member board, appointed by Governor, confirmed by Senate” (though created by the state, not a state-level governmental entity and not subject to regulation or oversight by any state entity but the Federal Energy Regulatory Commission (FERC); complies with NERC; part of Western Electricity Coordinating Council, WECC))	**Governance** “Board made up of 5 Commissioners appointed by the Governor and confirmed by the Senate. The Governor also designates a Chair and Vice Chair as primary agency leads.”	**Governance** “Consists of 14 members. 12 are appointed by, and serve ‘at the pleasure’ of the Governor along with the consent of the Senate. Two additional members are appointed by the Legislature, one by the Senate, the other by the Assembly”
Role for energy storage policy “Regulates and hence directly orders investor-owned utilities (IOUs), energy service providers (ESPs), and community choice aggregators (CCAs); key agency in charge of implementing California’s new electricity infrastructure; sets or influences most of the clean energy policies for the state and funds most of the electric sector programs”	**Role for energy storage policy** “Sets rules and approves interconnection of generation and storage to the CAISO-controlled grid	**Role for energy storage policy “**Primary energy policy and planning agency; prepares the Integrated Energy Policy Report (IEPR) and collaborates with state and federal agencies, utilities, and other stakeholders to develop and implement state energy policies.”	**Role for energy storage policy** “Has become a major force in California’s energy efforts besides dealing with local air pollution”
Staff ~1,000 **Budget** $136M (2015)	**Staff** ~1,000 **Budget** $195M (2017)	**Staff** ~1,000 **Budget** $387M (2012)	**Staff** 1,365 **Budget** $582M (2015)

Figure A.9: Overview of relevant governing entities for energy storage in California, 2016

Table A.4: Details on top down view of energy storage policy mix in California, 2016

Policy	Type	Brief Description of mechanism	Gov entity / ID	Since
Strategy				
Emission reduction				
EAP	Framework	The Energy Action Plan (EAP) suggests a "loading order" of investment priorities: 1. Energy efficiency and demand response, 2. Renewable and distributed generation, 3. Clean fossil-fueled sources and infrastructure improvements	CEC	2003
SB32, AB32	Emission reduction target	"Global warming solutions act"; stabilize GHG emissions in 2020 at 1990 levels, reduce GHG emissions by 80% by 2050	Senate	2016 (2006)
SB350	Emission reduction target	"Clean energy and pollution reduction act"; focus energy procurement decisions on reducing greenhouse gas (GHG) emissions by 40 percent by 2030, including efforts to achieve at least 50 percent renewable energy procurement, doubling of energy efficiency, and promoting transportation electrification	Senate	2015
B-30-15	Emission reduction target	reduce GHG emissions by 40% by 2030 compared to 1990 levels	Executive Order, Governor Brown	2015
SB185	Divestment	State's two largest pension funds divest from coal companies	Senate	2015
Energy innovation - Renewables				
SB1078	Renewable Portfolio Standard	Introduction of RPS; mandates state-regulated retail electricity sellers to purchase an additional 1% of retail sales per year from eligible renewable sources until 20% of sales is reached by 2017	Senate	2002
SB107	RPS Target	Mandates state-regulated retail electricity sellers to purchase 20% of retail electricity sales from renewables by 2010	Senate	2006
SB X1-2 (EO S-14-08)	RPS Target	New RPS applies to all electricity retailers in the state including publicly owned utilities (POUs), investor-owned utilities, electricity service providers, and community choice aggregators. All of these entities had to adopt the new RPS goals of 20 percent of retails sales from renewables by the end of 2013, 25% by the end of 2016, and the 33% requirement being met by the end of 2020.	Executive Order Governor Schwarzenegger; Senate	2008, 2011
AB327	Directive	Distributed resource plans (DRPs) to be handed in by state-regulated utilities by mid-2015; "DRPs are essentially blueprints for how Pacific Gas & Electric, Southern California Edison, and San Diego Gas & Electric are going to merge rooftop solar, behind-the-meter energy storage, plug-in electric vehicles and other distributed energy resources (DERs) into their day-to-day grid operations and long-range distribution grid planning and investment regimes" (GTM, 2015)	Assembly	2013
SB350	RPS Target	"Clean energy and pollution reduction act"; increases RPS to 50% met by the end of 2030 (50% of retail electricity sales from renewables by 2030)	Senate	2015

Energy innovation - Storage				
AB2267	Incentive Program	Increases SGIP incentive by 20% if eligible installation comes from a Californian supplier	Assembly	2008
AB2514	Directive	Directs the CPUC to "open a proceeding to determine appropriate targets, if any, for each load-serving entity to procure viable and cost-effective energy storage systems."; outcome: 1,325MW of energy storage to be procured by state regulated utilities	Legislator	2010
AB2868	Procurement Target	Increase AB2514 goals by 500MW	Assembly	2016
AB33	Procurement Target	As part of the long-term procurement planning process at the Public Utilities Commission, the ISO has identified a need for fast-ramping and flexible resources to balance the electrical grid and mitigate the effects of over-generation from renewable energy resources; The ISO has identified energy storage, with its unique ability to both utilize excess electricity generated by renewable energy resources and to quickly inject that electricity back onto the electrical grid to meet ramping and peak demand needs, as a part of the new strategy for efficiently operating the electrical grid in a manner that best protects the environment; the CPUC in coordination with the CEC, shall, as part of a new or existing proceeding, evaluate and analyze the potential for all types of long duration bulk energy storage resources to help integrate renewable generation into the electrical grid; As part of the evaluation, the commission shall assess the potential costs and benefits of all types of long duration bulk energy storage resources, including impacts to the transmission and distribution systems of location-specific long duration bulk energy storage resources	Assembly	2016
AB1637 (AB970, SB861)	Incentive Program	Doubles the budget of the self-generation incentive program (SGIP) from $83 million to $160 million annually	Assembly, Senate	2016 (2000, 2014)
Instruments				
CPUC				
IDER, IDSM	Directive	Mandates IOUs to integrate customer demand-side programs, such as energy efficiency, self-generation, advanced metering, and demand response, in a coherent and efficient manner	CPUC, D.07-10-032, R.14-10-003	2007
SGIP AES	Rebate Program	The Self-Generation Incentive Program (SGIP) provides upfront grants ($81M annually 2010-2014; extended until January 2021) for the installation of eligible technologies that are installed to meet all or a portion of the electric energy needs of a facility; includes "advanced energy storage" (AES) since D.08-11-044 from 2008; includes stand-alone AES since D.11-09-015 from 2011; purpose: to contribute to Greenhouse Gas (GHG) emission reductions, demand reductions and reduced customer electricity purchases, resulting in the electric system reliability through improved transmission and	CPUC D.01-03-073 (AB970, SB861, SB412, AB1478, AB1637)	2008

		distribution system utilization; as well as market transformation for distributed energy resource (DER) technologies.		
Rule21 Reforms	Grid or Market Access (Distribution/ Retail)	Improve distribution level interconnection rules and regulations (Electric Tariff Rule 21) for certain classes of electric generators and (new) electric storage resources	CPUC, R.11-09-011	2011
ES Procurement - IOU	Competitive Procurement	Mandates investor-owned utilities (IOU, state regulated) to procure 1,325MW (increased to 1,825MW in 2016) of viable and cost-effective energy storage systems; targets in T&D can also be reached via customer-sited projects	CPUC, R.10-12-007, R.15-03-11, D.16-01-032 (AB2514)	2013
AES RFOs	Competitive Procurement	Request for offers (RFOs) from IOUs to procure advanced energy storage (AES) systems provided by third parties; allows energy storage aggregators to bid into demand response procurement	CPUC, R.13-09.011	2013
DRAM pilot	Competitive Procurement	Third party demand response provider bids into CAISO energy (day-ahead + real-time) or ancillary service markets and receives capacity payment	CPUC, R.13-09.011	2013
IOU DR programs	Incentive Program	IOUs incentivizes customers to lower demand during called events; incentives may be offered to offset upfront costs or as reduced rates or both	CPUC, R.13-09.011	2013
DRP (ICA, LNBA)	Directive	Mandates IOUs to disclose bi-annually how they include distributed resources (among which distributed energy storage) into their planning and operations; data for resource allocation has been made available online (e.g. Integration Capacity Analysis (ICA) or Locational Net Benefit Analysis (LNBA)); ultimate goal: a plug-and-play grid for distributed energy resources	CPUC, R.14-08-013	2014
IRP, LTPP	System planning	Integrated resource and long term procurement plan	CPUC, R.16-02-007	2015
CAISO				
FERC 719 ,890	Market Access	Nondiscrimination of “new resources” (e.g. energy storage) for ancillary services	CAISO (FERC 719, 890)	2008
PDR	Market Access	Wholesale demand response product; Economically triggered “proxy demand resources” (PDR) may participate in CAISO Day-Ahead energy market (>100kW load curtailment), Day-Ahead and Real-Time Non-Spinning Reserve market (>500kW LC), and 5-Minute Real-Time Energy market (>100kW LC); load reduction may come from e.g. energy storage, HVAC, electric vehicles,… (not tracked or measured by CAISO)	CAISO Docket ER10-765-000 (FERC 719)	2010
NGR	Market Access	The implementation of “non-generator resources” (NGR) will create the initial model for energy storage devices to fully participate in ISO markets, and enable dispatchable demand response resources to participate in regulation	CAISO (FERC)	2011
FERC755	Pay-for-performance requirement	Increases the pay for “fast” responding sources like batteries or flywheels that are bidding into frequency regulation service markets	CAISO (FERC)	2011
FERC784	Pay-for-performance requirement	Increases the pay for “fast” responding sources like batteries or flywheels that are bidding into ancillary services market	CAISO (FERC)	2013

FERC792	Directive	Revises FERC's Small Generator Interconnection Procedures and Small Generator Interconnection Agreement to expressly include storage devices	CAISO (FERC)	2013
RDRR	Market Access	Wholesale demand response product; Modeled like a supply resource relying on the functionality and infrastructure designed for proxy demand resources (PDR); resolves issues concerning quantity, use and resource adequacy treatment of retail emergency*-triggered demand response programs; "reliability demand response resources" (RDRR) may participate in CAISO Day-Ahead Market, and respond to a reliability event for the delivery of "reliability energy" in real-Time; load reduction may come from e.g. energy storage, HVAC, electric vehicles,… - not tracked or measured by CAISO; (*Reliability-only uses include: system emergencies (transm. emergencies on ISO controlled grid, mitigation of imminent or threatened operating reserve deficiencies), local T&D system emergencies)	CAISO (FERC), CPUC	2014
FERC 764	Market Design (Wholesale)	Introduction of intra-hour transmission scheduling: 15-minute market with financially binding energy and ancillary services awards for internal generators, imports and exports and participating loads; these market changes reduce barriers to integrating variable energy resources (e.g. storage) and addressed known market inefficiencies	CAISO (FERC)	2014
WDAT	Grid or Market Access (Transmission/ Wholesale)	Introduces distinction between energy consumption, and intermediate storage, the latter being treated as a generation device; market activities will be settled at the wholesale market locational marginal price	CAISO (FERC)	2014
ESISI	Information	Energy storage interconnection stakeholder initiative (ESISI); assessment of whether changes to existing ISO rules are needed to accommodate storage.	CAISO (FERC)	2014
ESDER	Information	Energy storage and distributed energy resources (ESDER) stakeholder initiative; enhance ability of ISO and distribution-connected resources to participate in ISO market	CAISO (FERC)	2015
DERP	Market Access	Creates a new class of grid market players, namely distributed energy resource providers (DERPs) and allows them to aggregate DERs and participate in CAISO energy or ancillary service markets as "non generating-resources" (NGR); requirements: participating generator agreement (PGA) and participating load agreement (PLA); additionally, NGRs are ISO metered entities (ISOME) which fall under the corresponding compliance requirements; all utility interconnection requirements need to be met which may include the need to obtain a WDAT interconnection, similar to any other generator connected at the distribution level that participates in the wholesale market	CAISO (FERC)	2015
CEC				
PIER	R&D support	The Public Interest Energy Research (PIER) program helped improve energy efficiency technologies and strategies; received roughly	CEC, AB1890	1996-2013

		$62.5 million annually in surcharges on electricity rates and $24 million per year in surcharges on natural gas rates; provided contract or grant funding e.g. for energy storage R&DD, e.g. making evaluation tools and methodologies transparent and publicly available		
Bi-annual IEPR	R&D support	Every 2 years, the CEC needs to file an "Integrated Energy Policy Report" (IEPR) to inform the Governor and Legislature about recent energy policy advances in California	CEC, D#02-IEP-1ff, SB1389	2003
EISG ESI	R&D support	The Energy Innovations Small Grant (EISG) Program ($2.6M annual budget) provides up to $150,000 for hardware projects and $75,000 for modeling projects to small businesses, non-profits, individuals and academic institutions to conduct research that establishes the feasibility of new, innovative energy concepts; Research projects must target one of the PIER R&D areas, address a California energy problem and provide a potential benefit to California electric and natural gas ratepayers; Subject Area - Energy Systems Integration (ESI) (formerly "Strategic Energy Research"): "Cross-cutting" strategic energy RD&D activities could include system-related projects that utilize renewables, environmentally preferred advanced generation, energy efficiency and environmental technologies in an integrated manner. RD&D activities related to grid reliability, safety and capacity, energy related tools and assessment technologies also fall within the ESI subject area.	CEC	2007
ES Procurement - POU	Information	Mandates publicly owned utilities (POU, municipality regulated) to develop procurement goals and report targets, progress reports, and policies adopted by its governing board to the Energy Commission	CEC, AB2514	2013
Inter-agency				
EPIC (SHINES, AES)	R&D support	Electric Program Investment Charge (EPIC); the most comprehensive statewide approach to creating new energy solutions, fostering regional innovation and bringing ideas to the marketplace; EPIC consolidates the R&D initiatives of the three largest investor-owned utility service areas into an aggregate program, which ensures no duplication in spending and also implements compliance with state energy policies; grant funding for RD&D in e.g. energy storage; past: $10M for Sustainable and Holistic Integration of Energy Storage and Solar PV (SHINES); $12M for Developing Advanced Energy Storage Technology Solutions to Lower Costs and Achieve Policy Goals (AES); future: Triennial Investment Plan ($26M, 2015-2017) - Goal S15: "Demonstrate Advanced Energy Storage Interconnection Systems to Lower Costs, Facilitate Market and Improve Grid Reliability"	CPUC, CEC, PON-14-308, DE-FOA-0001108; PON-13-302	2013
ES Roadmap	Information	The report "Advancing and maximizing the value of energy storage technology, a California roadmap" was developed with more than 400 stakeholders and clarifies and prioritizes specific or shared deliverables by each of the three state	CAISO, CEC, CPUC	2014

		agencies CPUC, CEC, CAISO in order to "maximize the value of energy storage technology"		
RA Program	System planning	The resource adequacy program provides sufficient resources to the CAISO to ensure the safe and reliable operation of the grid in real time, as well as appropriate incentives for the siting and construction of new resources needed for reliability in the future; latest rulemaking includes establishment of annual local and flexible procurement obligations	CAISO, CPUC, R.14-10-010	2014

Table A.5: Details on bottom up down view of policies affecting the economics of residential solar+storage in California, 2016

Policy	Type	Brief Description of mechanism	Gov entity / ID	Since
Instruments				
Federal				
ITC-PV/BS	Tax Incentive Program	The Investment Tax Credit (ITC), is one of the most important federal policy mechanisms to support the deployment of solar energy in the United States; under the ITC (or officially the "Residential Renewable Energy Tax Credit") a taxpayer may claim 30% of the investment into a "solar dwelling unit" as expenditures on the tax statement (phased down until 2023); potentially includes tax credit for battery storage, but: limited to 27% tax credit due to dual-use capability; at least 75% of stored energy in year 1 must come from solar PV)	U.S. Internal Revenue Service (IRS), Code 25D; American Recovery and Reinvestment Act (ARRA) 2009	2015 (2006)
ITC-HP	Tax Incentive Program	Under the Residential Energy Efficiency Tax Credit (ITC-HP) a taxpayer may claim US$300 of the investment into an "Electric heat pump water heater with an energy factor of at least 2.0" as expenditures on the tax statement	U.S. Internal Revenue Service (IRS), Code 25C; American Recovery and Reinvestment Act 2009	2015 (2011)
State				
Group 1				
Electricity RD	Rate design	The CPUC approves the amount that each electric utility can collect from its customers. This is a utility's "revenue requirement" and it is based on the cost of operating, maintaining, and financing the infrastructure used to run the utility; and on the cost of its procured fuel and power	CPUC, PUC sections 451, 748; R.12-06-013, electric utilities	2015 (1911)
Gas RD	Rate design	The California Public Utilities Commission (CPUC) regulates natural gas utility service for approximately 10.8 million customers	CPUC, PUC section 451, natural gas utilities	2015 (1911)
Electricity TCL	Consumption Levies	Taxes, charges, and levies (TCL) on electricity consumption; $1.94ct/kWh PUC reimbursement fee, energy resources surcharge, publich purpose program charge, new system generation charge, nuclear decommissioning charge, competition transition charge	CPUC, PUC section 748, Utilities, Board of Equalization (BoE), electric utilities	2015 (1911)
Gas TCL	Consumption Levies	Taxes, charges, and levies (TCL) on gas consumption; $0.37ct/kWh natural gas surcharge and state regulatory fee	CPUC, PUC section 748, Utilities, Board of Equalization (BoE), SB695, natural gas utilities	2015 (1911)
Group 2				
NEM	Directive	Net energy metering (NEM) encourages private investment in renewable energy resources ; NEM is a billing arrangement for costumers offered by electric utilities under instructions from the Californian Pubic Utilities Commission (CPUC); introduced in 1996 it allows prosumers with the eligible renewable generation technology to	CPUC, AB58 (cost&benefit analysis), AB 920 (NSCR), AB327 (NEM successor), D.16-01-044 (one time	2016 (1996, 2002, 2013, 2015)

		receive remuneration at retail value for electricity fed to the grid, a level which significantly exceeds standard wholesale PV electricity rates and the value to the purchasing utility; NEM program rules and regulations allow regulators and utilities to provide transparent, simplified and expedited interconnection procedures for small customers; "all ratepayers pay for the NEM program in the form of billing credits, administrative costs, and interconnection costs, and all ratepayers receive some benefit from the NEM program in the form of avoided capacity and avoided RPS purchases" (CPUC, SB695 report 2012, p.34); AB 327 requires the CPUC to balance the ratepayer costs of the program with the need to maintain a growing and sustainable distributed generation industry	interconnection fee, non bypassable charges), R.14-07-002	
NEM NSC	Directive	At the end of a customer's 12-month billing period, any balance of surplus electricity is trued-up at a separate fair market value, known as net surplus compensation (NSC). The NSC rate is based on a 12-month rolling average of the market rate for energy, or approximately $0.04 to $0.05 per kilowatt-hour	CPUC D.11-06-016 (AB920)	2009
NEM ES	Directive	Clarifies that storage facilities may be treated as an addition or enhancement to renewable generation and hence receive the same benefits as distributed generation facilities (no interconnection application fees, supplemental review fees, costs for distribution upgrades, and standby charges); small scale storage systems (<10kW) are also excluded from the requirement of installing additional metering devices or a non-export relay; instead small paired (PV+storage) facilities should be permitted to use an estimation methodology based on a presumed generation profile of the generating facility's NEM generator to validate the eligible NEM credits accrued to the generating facility	CPUC, R.12-11-005, D.14-05-033	2015
Group 3				
SGIP AES	Rebate Program	The Self-Generation Incentive Program (SGIP) provides upfront grants ($81M annually 2010-2014) for the installation of eligible technologies that are installed to meet all or a portion of the electric energy needs of a facility; includes "advanced energy storage" since Decision 08-11-044 from 2008; purpose: to contribute to Greenhouse Gas (GHG) emission reductions, demand reductions and reduced customer electricity purchases, resulting in the electric system reliability through improved transmission and distribution system utilization; as well as market transformation for distributed energy resource (DER) technologies.	CPUC D.01-03-073 (AB970, SB861, AB1478, AB1637)	2008
Group 4				
Sales Tax	Tax & Levies	California sales tax is imposed on all California retailers and applies to all retail sales of merchandise (tangible personal property) in the state; increases investment cost by 7.5-10%	Board of Equalization (BoE), Revenue and Taxation Code	2016

PTE	Tax & Levies	Allows a property tax exclusion (PTE) for certain types of newly constructed "active solar energy systems"; qualifying systems are defined as those that "are thermally isolated from living space or any other area where the energy is used, to provide for the collection, storage, or distribution of solar energy.	Board of Equalization (BoE), California Revenue and Taxation Code Section 73, County assessor's office, AB1451, ABX1-15	2008 (1999)
Local				
PII	Grid or Market Access (Distribution/ Retail)	Permitting, inspection, and Interconnection (PII) fees; for an average U.S. household these soft cost items increase total residential system installation costs by about 3.6% (NREL, 2013)	Municipality, Authority having Jurisdiction (AHJ)	2013
Strategies				
Behind ITC				
EPACT	Framework	Energy Policy Act; provides financial support via investment and production tax credits as well as loan guarantees for eligible energy production technologies; the Energy Policy Act (EPACT) of 2005 required state utility regulators (outside of California) to consider NEM	Passed both House and Senate; enacted by President Bush	2005
EIEA	Framework	The Energy Improvement and Extension Act of 2008 (EIEA) is part of the Emergency Economic Stabilization Act of 2008; it provides financial support via specific tax credits or incentives to support	Passed both House and Senate; enacted by President Bush	2008
ARRA	Fiscal policy response	American Recovery and Reinvestment Act; immediate goal was to stabilize the economy, preserving and restoring jobs, and assisting deeply suffering industries; ARRA appropriated $787 billion at the time of passage, and this was later revised to $831 billion over the 2009 to 2019 period. Of the initial allocations, $90 billion was allocated towards investing in a cleaner, more sustainable energy future among which e.g. Advanced Research Projects Agency-Energy (ARPA-E) program to support early-stage innovations; investments can be seen as a "down-payment" on the transition to a sustainable 21st century economy, and each has an economic rationale based on addressing multiple market failures, such as environmental externalities and innovation market failures.	Passed both House and Senate; enacted by President Obama	2009
Behind rate design				
PUA	Constitutional Amendment	The Public Utilities Act (PUA) expands the "Railroad Commission's" regulatory authority to include natural gas, electric, telephone, and water companies as well as railroads and marine transportation companies; today, the CPUC (renamed in 1946) regulates privately owned electric, natural gas, telephone, water, and sewer utilities	Legislature	1912
Behind NEM				
Deregulation	Directive	Deregulate the state's investor-owned electric utilities in order to increase competition, and drive down electricity and gas prices. Create incentives for grid-tied PV systems under the CEC's Renewable Energy Program	AB1890 (Electric Utility Industry Restructuring Act), SB656	1996

PUC2827	Directive	Encourage investment in distributed generation and develop a self-sustaining market for "emerging" renewable energy technologies in distributed generation applications	PUC section 2827	1996
RESIA	Directive	Reliable Electricity Service Investments Act	AB995, SB1194, SB1038, Governor Wilson	2000
AB327	Directive	Ensure that customer sited renewable distributed generation continues to grow sustainably beyond 5% NEM program limit or past eligibility time frame of July 2017; ensure that the successor tariff is based on the costs and benefits of the renewable electrical generation facility; ensure that the total benefits of the tariff to all customers and the electrical system are approximately equal to the total costs; establish terms of service and billing rules for eligible customer generators, consistent with all other relevant statutory requirements.	Assembly, Governor Brown	2013
Behind SGIP				
AB970	Directive	Assembly Bill required the CPUC to initiate load control and distributed generation (DG) activities; DG technologies include internal combustion engines, micro turbines, small gas turbines, wind turbines, photovoltaics, fuel cells, and combined heat and power or cogeneration	Assembly	2000
D.08-11-044	Decision	Determined that Advanced Energy Storage systems coupled with eligible SGIP technologies will receive an incentive of $2/watt of installed capacity.	CPUC	2008
SB861	Directive	Extended SGIP funding through 2019 and extended SGIP administration until January 1, 2021; directed the Commission to update the factor for avoided greenhouse gas emissions based on the most recent data available to the State Air Resources Board; established eligibility requirements for distributed technologies that: reduce demand from the grid by offsetting some or all of the customer's onsite load, are commercially available, safely utilize the existing T&D system, and improve air quality by reducing criteria air pollutants; changes the California supplier requirement to "manufactured in California"	Senate	2014
AB1478	Directive	Clarified that eligible technologies can shift onsite energy use to off-peak times	Assembly	2014
AB1637	Directive	Doubles the budget of the self-generation incentive program (SGIP) from $83 million to $160 million annually	Assembly	2016
Behind Taxes				
BOE	Constitutional Amendment	Established in 1879 by a constitutional amendment, the Board of Equalization (BOE) was initially charged with responsibility for ensuring that county property tax assessment practices were equal and uniform throughout the state. Currently the tax programs administered by the BOE are concentrated in four general areas: sales and use taxes, property taxes, special taxes and the tax appellate program; In 2012-13	Legislature	1879

		BOE-administered taxes and fees generated $56 billion to provide essential services for the people of California. BOE administered programs accounted for more than 30 percent of all state revenue.		
Behind PII				
AHJ	-	Depends on "Authority Having Jurisdiction" (AHJ), e.g. municipality	-	-

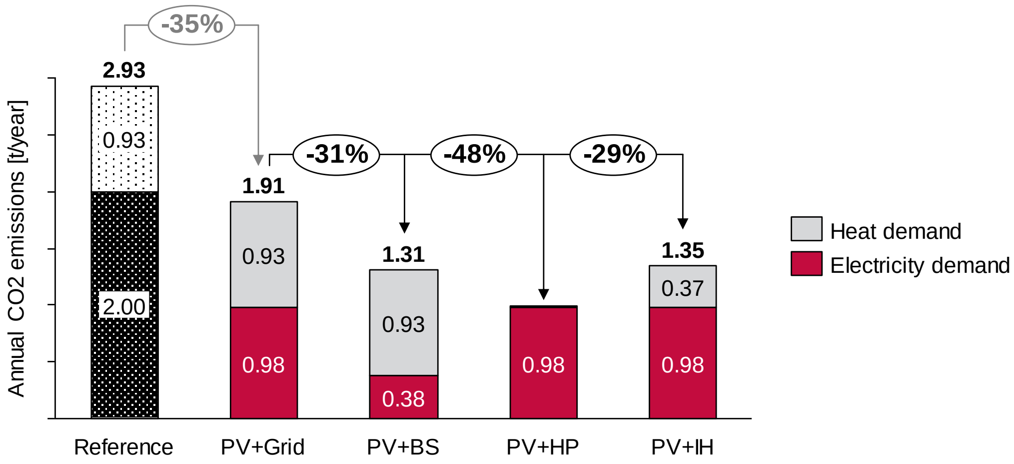

Figure A.10: CO2 emission reduction potential of three selected energy storage systems tied to a solar PV system; results of techno-economic simulation of single-family household in California; assumption: CO2 intensity of energy service demands (power + heat) determined by California's electricity mix (268 g/kWh, EIA, 2014) and efficiency of natural gas boiler (82%), respectively

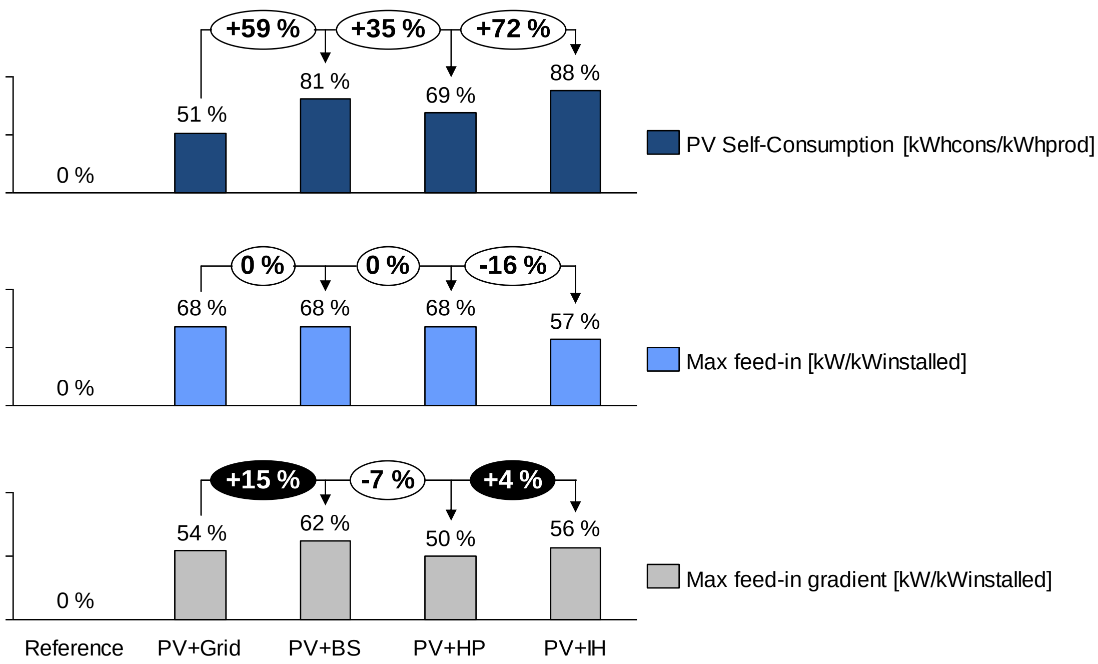

Figure A.11: Two exemplary proxies for the renewable integration potential of three selected energy storage systems tied to a solar PV system; results of techno-economic simulation of single-family household in California

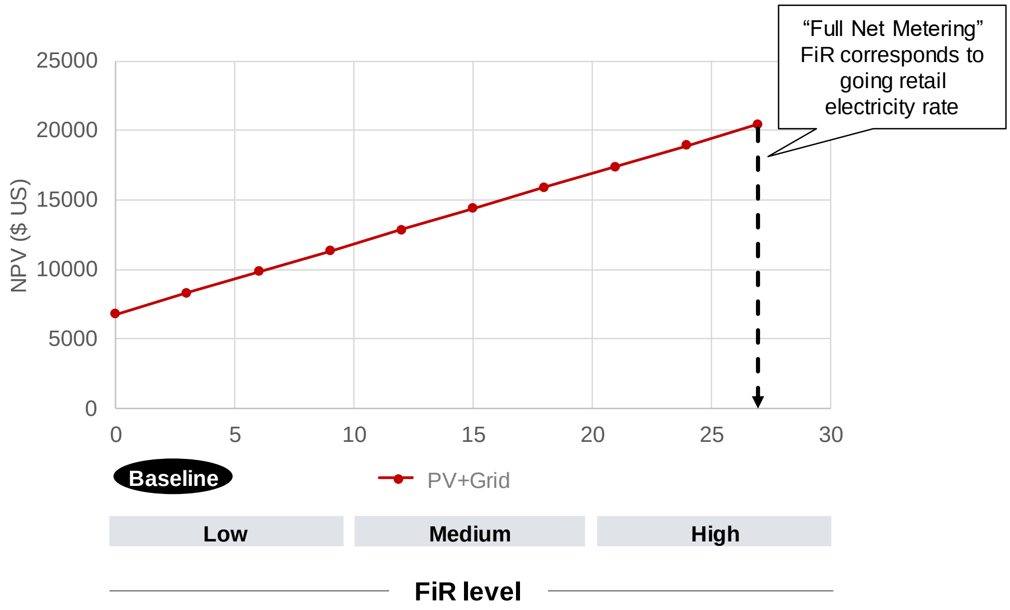

Figure A.12: Baseline scenario for techno-economic analysis: NPV of investment into "stand-alone solar PV"

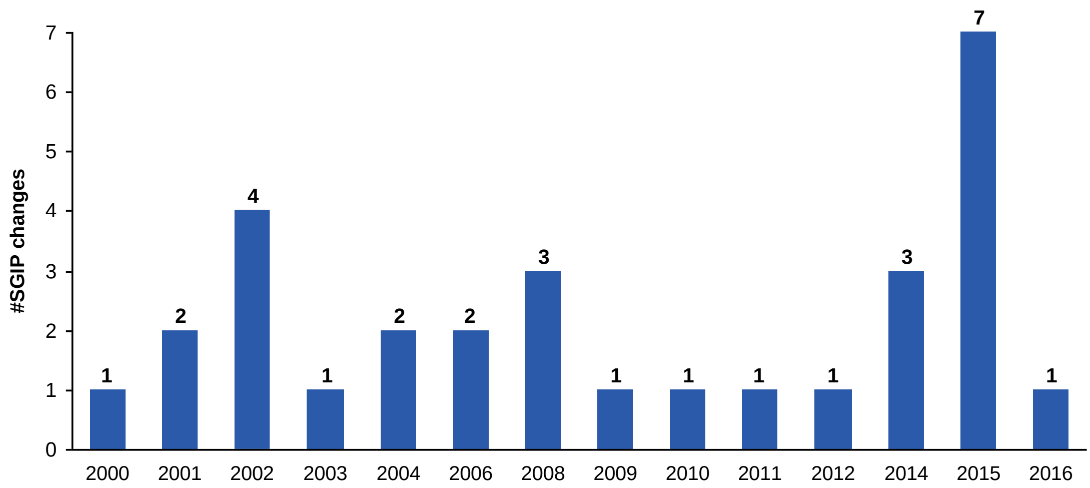

Figure A.13: Number of amendments to California’s “Self-Generation Incentive Program” (SGIP); Own illustration based on data provided in “SGIP Handbook 2016” (CSE et al., 2016, p. 81ff)

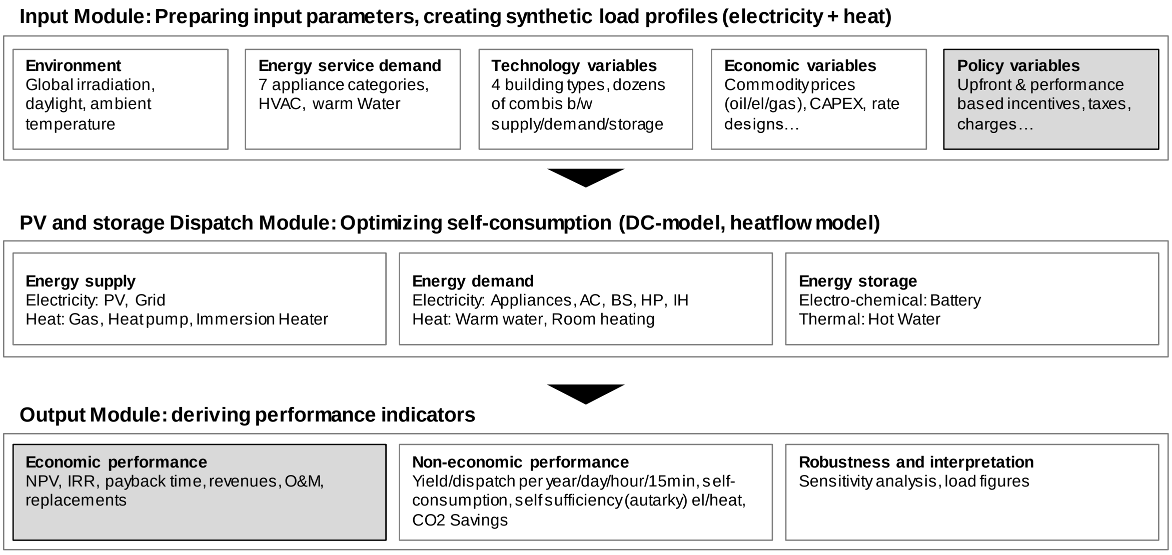

Figure A.14: Conceptual layout of the building simulation model; own code implemented in Mathworks MATLAB

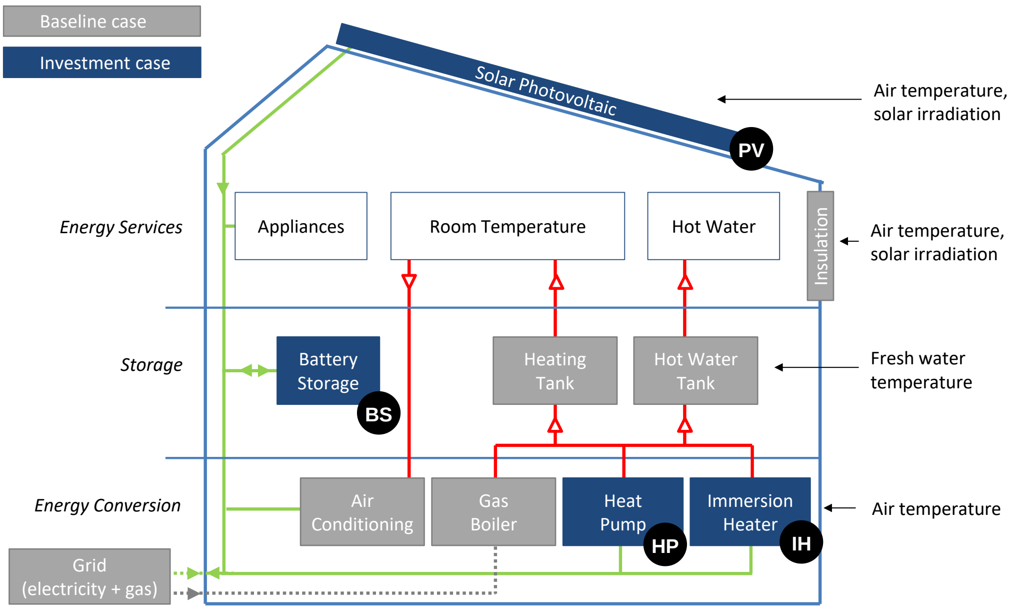

Figure 15: Overview of the focal technological components covered by the techno-economic simulation of the building type "single-family house"; determines input parameters for "energy service demands", "technology variables", "economic variables", and "policy variables" Figure A.14

	Supply		Demand		Storage	
	Electricity	Heat	Electricity	Heat	Electricity	Heat
Reference	Electricity Grid Grey mix (PG&E, Tariff Bakersfield)	5.3kWp gas boiler 82% efficiency 0$/kWp unltd. a	HVAC, ICT, lighting, dishwasher, washing machine, dryer, cooking, fridge, freezer ~7,000kWh/a	Room heating 23°C, 150m² Warm water 4 residents, 1 party ~4,500kWh/a	None	200l room heating 1000l warm water
PV+Grid	Baseline + 4.5kWpeak 15% efficiency 3088$/kWp 25a				Grid (virtual)	
PV+BS					3.3kW, 7kWh 90% efficiency 1030$/kWh 12a, 10250c	
PV+HP		Baseline + 4.5kWp air-sourced HP Dyn. Efficiency 550$/kWp 17.5a			Grid (virtual)	
PV+IH		Baseline + 3kWp fully controllable IH 99% efficiency 154$/kWp 13a				

Figure A.16: Overview of techno-economic input parameters; market data for California (2015) retrieved from archival data research

Paper IV

Conference Paper at Eu-SPRI (2017) and IST (2017)

(Targeted towards Nature Energy)

How Policy shapes the Diffusion of Residential PV+Battery Systems An Agent-based Simulation of California's Energy Transition

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Abstract

Distributed solar PV systems, such as residential rooftop solar, have become increasingly relevant as a building block in the energy transitions of countries around the world. However, beyond a certain penetration of solar PV in the system, complementary technologies, such as battery storage systems, are required that allow system operators to balance out renewable intermittency and maintain security of supply. Given it is unlikely that these technologies diffuse fast enough in light of the decarbonization challenge, policymakers have started to intervene using specific policy instruments that spur the demand for residential "PV+battery" systems. However, the complex interplay between these policies with a number of social, technological, and economic drivers renders estimating the combined effect on technology adoption an intricate task. Therefore, this paper assesses how alternative policy mixes (bundles of strategic policy goals and policy instruments) affect the diffusion of residential PV+battery systems. To do so, the three most relevant policy instruments are taken into account, namely upfront support, electricity rate design, and feed-in remuneration. Building on an agent-based simulation of California's electricity sector – one of the largest and fastest growing markets for distributed solar PV in the world – we elaborate on the diffusion of residential PV+battery systems between 2005 and 2030. In particular, we study three particular policy mix designs and assess their effect on PV+battery diffusion as well as their systemic impact in terms of the grid infrastructure and cross-subsidization between ratepayers. The analysis entails valuable insights for policymakers in California and beyond, as well as an important methodological contribution for the policy mix literature.

Keywords

Policy Mix; Policy Design; Technological Change; Technology Diffusion; Policy Goals

1 Introduction

In recent years, accommodating large amounts of small-scale, spatially distributed, and intermitted energy generation based on renewable resources has become a cornerstone of climate change strategies in numerous countries. Residential solar photovoltaic (PV) systems are a prominent example of such technologies, which have seen rapid deployment over the last decade (IRENA, 2015; Reichelstein and Yorston, 2013; Sivaram and Kann, 2016). From a micro-economic standpoint, this development was driven by the confluence of high residential retail electricity rates, policy support schemes, and substantial decreases in PV system costs due to scale and learning effects (Huenteler et al., 2016; Rickerson et al., 2014). However, while residential solar PV entails the potential to become an important building block in the changing electricity mix of many countries, two central challenges evolve around a) how to integrate high penetrations of distributed solar PV into an evolving electricity system (Stanfield and Vanega, 2015), and b) how to allocate the associated costs and benefits equitably across customers (Borenstein, 2011; Fürstenwerth et al., 2015). Both challenges arise from the fact that the existing electricity system in many countries was designed around electricity generation in large-scale, centralized, and controllable power plants, often based on fossil fuels (Burger and Weinmann, 2013). While the examples of California, Germany, and Hawaii show that the existing infrastructure may provide the flexibility to accommodate solar PV penetrations in the range between 20-30% of peak capacity, there will be limitations when it comes to further increasing deployment of solar PV systems (Kondziella and Bruckner, 2016; Martinot, 2016).

The former – technological challenge – has broadly two aspects: First, the distributed nature of electricity generation from PV is problematic for a grid designed for centralized generation, at least without considerable investments into the transmission and distribution (T&D) infrastructure. Second, PV generation does generally not perfectly match onsite demand which results in abrupt system-wide load increases especially in the late afternoon hours and entails the need for fast-ramping capacity, usually met by conventional – often fossil – peaking power plants. To address both issues, stationary battery storage systems (BSS) enable solar PV owners to increase consumption behind-the-meter (BTM), which simultaneously reduces the need for T&D infrastructure upgrades as well as fast-ramping generation in front of the meter (FOM). In sum, the combination of residential solar PV and battery systems, i.e. "PV+battery systems", can be seen as a stepping stone for the next phase of solar PV deployment (Fitzgerald et al., 2015; Kempener and Vivero, 2015; Moshoevel et al., 2015).

The latter – cross-subsidization challenge – arises from the fact that, to date, the costs that arise from investing into, operating, and maintaining the electricity grid are mostly covered on a volumetric basis, as part of consumers' electricity bills. With an increasing number consumers investing into solar PV rooftop systems, these users can reduce their energy demand, and thus bypass many of the aforementioned costs. As a consequence, these costs need to be covered by the rest of the rate payers which may ultimately lead to cross-subsidization between different ratepayer groups. Such cross-subsidization could be further elevated through PV+battery systems, which allow homeowners to increase the share of PV generation consumed onsite compared to stand-alone PV systems (Bronski et al., 2015; Merei et al., 2016).

The nature of these challenges puts public policy makers and electric utility regulators into the dilemma, that addressing one challenge will ultimately elevate the other. For example, given the increasing technological maturity of solar PV systems, policy makers have started to lower the amount of remuneration solar homeowners receive for feeding electricity into the public grid (Hoppmann et al., 2014b). While this, in turn, may spur the deployment of BSS (cf. challenge a), it may not lead to the desired reduction in cross-subsidization between PV owners and other customers, thereby aggravate challenge b.

The presence of such multiple policy goals[1], the interaction[2] among policy schemes, as well as the dynamic interplay[3] between policies and technological innovation and diffusion, renders assessing and developing policy mixes an intricate task (Del Río and Howlett, 2013; Flanagan et al., 2011; Rogge and Reichardt, 2016). However, accurately depicting these mechanisms and elaborating on realistic scenarios for the deployment of renewable energy systems is invaluable for a number of stakeholders. These include policymakers in charge of governing the socio-technical transition of the energy sector (Markard et al., 2012), grid operators responsible for running the transmission and distribution infrastructure (Mills et al., 2016; Moshoevel et al., 2015), private firms facing a rapidly changing regulatory environment with fundamental implications for their evolving business models (Barbose et al., 2016), as well as end-consumers who ultimately cover the largest share of the costs (Darghouth et al., 2016a).

For the emerging residential PV+battery ecosystem, literature has identified and assessed many important policy instruments and scrutinized their impact on a range of technical or micro-economic aspects such as optimal sizing, operation modes, levelized cost of energy, or payback periods (Comello and Reichelstein, 2016; Darghouth et al., 2011; Reichelstein and Sahoo, 2015; Taylor, 2008). However, most of these studies abstract from the fact that policy instruments are part of a larger policy mix and may interact with each other (Rogge and Reichardt, 2016). Furthermore, studies assessing the impact of policies ex ante often assume policies to be exogenously given, when in reality, the design of policy mixes co-evolves depending on development of the underlying socio-technical transition (Hoppmann et al., 2014a). In addition, while there are some studies that analyze system-level feedback[4] loops induced by the diffusion of residential solar PV, many of them focus on stand-alone systems (Cai et al., 2013; Darghouth et al., 2016b) while abstracting from their potential combination with stationary storage systems such as batteries (Fitzgerald et al., 2015; Hledik et al., 2016; Hoppmann et al., 2014b). Last but not least, most of the before mentioned research abstracts from

[1] e.g. timely decarbonization, technological innovation, limiting costs to the public

[2] e.g. the level of feed-in remuneration being set at the going retail electricity rate

[3] e.g. an upfront grant phasing out based on the deployment rate of a given technology

[4] e.g. changing both supply and demand in the electricity wholesale market

the fact that aspects other than techno-economic characteristics, such as individual preferences and local adaptation (e.g. neighborhood effects) play an important role in consumer adoption decisions, which is particularly relevant for the case of solar PV and BSS (Sigrin et al., 2016). For example, a survey among private homeowners in Germany who had installed a solar PV and BSS system reveals that non-monetary incentives such as "becoming a part of the energy transition" or "interest in the novel technology" may outweigh the importance of economic viability of these projects (Kairies et al., 2016, p. 63ff).

Given the absence of an integrated, ex ante assessment of the interplay between alternative policy designs and the emerging PV+battery ecosystem, this paper investigates how three particular policy instruments affect the diffusion of residential solar PV and battery systems in California between 2005 and 2030. To do so, we build on an agent-based model which allows us to quantify and elaborate on alternative policy mixes that are composed of the three most relevant policy instruments affecting the economics of residential solar PV and BSS, namely upfront support schemes, retail rate design, and feed-in remuneration.

The remainder of the paper is structured as follows. Section 2 provides an introduction into our research setting – the residential electricity market in California. Section 3 outlines the agent-based modelling approach, its calibration, and the focal policy mix designs. Section 4 examines the model outputs and discusses the relevant implications for the literature.

2 Research Setting

As our research setting we select the state of California (USA), which is particularly well suited to assess how policy affects the diffusion of residential solar PV and battery systems for the following three reasons. First, California is home to the largest residential solar PV market and capacity installed in the United States, which allows us to calibrate our model on comprehensive longitudinal data (Barbose and Darghouth, 2016; EIA/DOE, 2016; Pyper, 2016). As such, it is one of the first regions to experience system-wide challenges associated with the integration of intermittent renewables, e.g. the significant change in the daily residual load pattern called “duck curve”, which indicates an increasing need for fast-ramping generation in the late afternoon hours (CAISO, 2016). Hence, in order to reach the state’s ambitious energy transition milestones (e.g. 50% renewables and 40% GHG reduction until 2030), significant investments into the existing energy infrastructure will be necessary. To accommodate an increasing share of renewable generation, the Californian government has started to support the diffusion of energy storage systems, e.g. via procurement targets (AB2514), which has resulted in a rapid uptake of the market and turned California into the “hotbed” for innovative energy storage vendors.

Table 1: Overview of policy instruments affecting the economics of residential solar PV and battery systems

	Policy instrument	Option	Unit	Name	In effect	Data sources
PI1 Upfront support	Grant_PV	-	US $/W	CSI[1]	2007-2014	CSI Website
	Grant_Battery	-	US $/W	SGIP[2]	2008-2020	SGIP Website
	TaxCredit_PV	-	-	ITC[3]	2006-2022	IRS
	TaxCredit_Battery	-	-	ITC	20XX-2022	IRS
PI2 Rate Design	Volumetric	Flat	US ct/kWh	-	-	IOUs, CPUC
		Tiered, 5 blocks	US ct/kWh	-	2001-2016	IOUs, CPUC
		Tiered, 3 blocks	US ct/kWh	-	2016-20XX	IOUs, CPUC
		TOU	US ct/kWh	TOU[4]	2019-*	IOUs, CPUC
	Fixed charges	-	US $	-	-	IOUs, CPUC
	Demand charges	-	US $/Wp	-	-	IOUs, CPUC
PI3 FiR Design	Volumetric	NEMFactor	-	NEM[5]	1996-2019	CPUC
		FIT	US ct/kWh	FIT	-	POUs, Own

[1] ”California Solar Initiative”; [2] ”Self-Generation Incentive Program”; [3] ”Federal Investment Tax Credit”; [4] ”Time-of-Use Rate”; [5] ”Net Energy Metering”

Second, over the last decade, several different instruments have established a policy mix that specifically affects the emerging residential solar PV and energy storage ecosystem in California (Darghouth et al., 2016b; Sivaraman and Moore, 2012). An outline of the most relevant policy instruments that directly affect the economics of residential PV+battery systems is provided in Table 1.

The instruments fall into three categories of instruments, namely upfront support schemes that lower the investment costs (*PI1*), retail electricity rate designs that determine the composition of the electricity bill of residential customers (*PI2*), and feed-in remuneration schemes that determine the level of compensation paid for PV exported to the grid (*PI3*). Since the interactions between the individual policy measures and their design features are non-trivial, and as they are likely to undergo amendments over the next years, studying the impact of this evolving policy mix holds valuable implications for both policy makers in California and beyond.

Third, California's retail electricity market is highly regulated. In particular, electricity prices for residential customers are negotiated according to a clearly defined routine between electric utility companies and California's Public Utilities Commission (CPUC), namely a "General Rate Case" that unfolds on a triennial basis. This aspect provides us with a blueprint for how to incorporate the feedback loop between solar PV and battery storage deployment and retail electricity tariffs.

3 Methodology and Data

Since economics are only one factor that explains why consumers adopt a novel technology, we employ an agent-based modelling approach to incorporate additional behavioral aspects. Agent-based models have previously been applied in a range of disciplines such as ecology (Grimm and Railsback, 2005), ecosystem management (Janssen, 2002), and economics (Tesfatsion and Judd, 2006). They build on the idea that to understand the dynamics of socio-technical systems one needs to understand the decisions, behavior, and interaction of the actors that are part of it (Miller and Page, 2007). Instead of modelling system behavior at the aggregated level, agent-based modelling opens the black box of socio-technical systems to understand how system behavior emerges from the complex interplay of heterogeneous and learning agents (Gunderson and Holling, 2002). As a result, agent-based modelling is well suited to capture the complex socio-technical dynamics, such as adaptation and local interaction, that emerge under the different focal policy scenarios (Bale et al., 2015). In this section we first describe the model in detail, briefly elaborate on the model calibration, and present the scenarios simulated.

3.1 Agent-based model description

In building our model, we followed the ODD (i.e. overview, design principles, details) protocol (Grimm et al., 2010, 2006), which ensures a systematic model development and documentation. Figure 1 conceptually outlines our approach, including inputs, socio-technical model, and outputs. The model aims at representing residential solar PV and battery storage deployment in California under different policy scenarios and in light of the two challenges introduced above, namely (a) the need for fast-ramping generation capacity – smoothing the "duck-curve" – and T&D infrastructure upgrades, and (b) the issue of cross-subsidization between ratepayers.

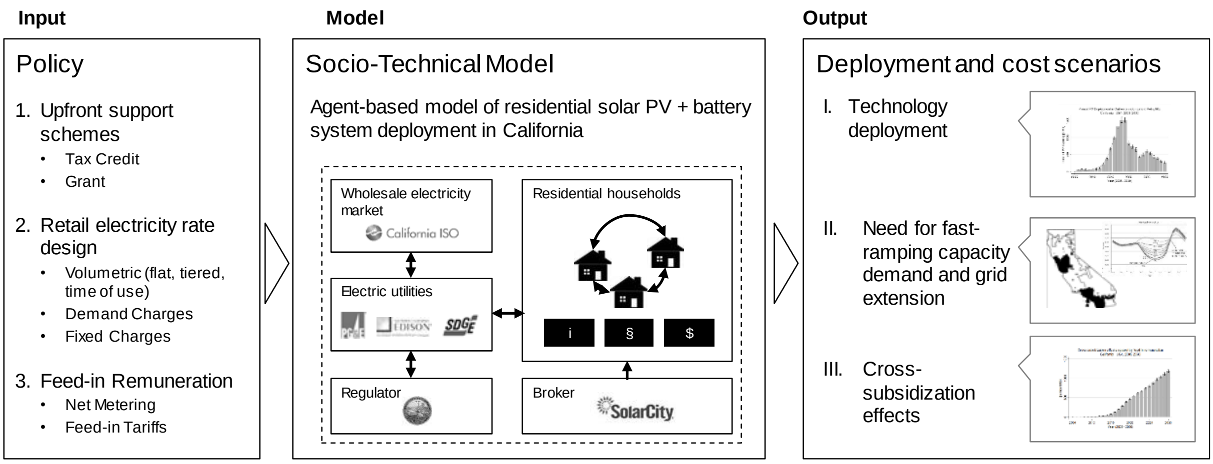

Figure 1: Overview of the agent-based model of residential solar PV + battery storage adoption

Model output

Consequently, the three key outputs of the model are: (i) technology deployment, (ii) grid impacts, and (iii) cross-subsidization effects.

i. Technology deployment is measured as:
   a. The annual and cumulative installed capacity of PV [MWp] and BSS [MWh] systems
   b. The cumulative electricity generation from all PV systems until 2030 [GWh]
   c. The share of total PV, PV stand-alone, and integrated PV+battery system adopters in 2030 [%]

ii. Grid impacts are indicated with:
   a. The need for fast-ramping generation capacity, i.e. the four-hour pre-peak differential in the system load [MW/h]
   b. The electricity grid congestion, i.e. percentage of population living in areas where PV feed-in exceeds 50% of total local load in 2030 [# households in m]

iii. Cross-subsidization effects are approximated by:
   a. The total amount of feed-in remuneration PV adopters receive, i.e. utilities' costs for buying electricity from PV adopters instead from wholesale electricity market [$]
   b. The total amount of utilities' fix-costs being redistributed from PV adopters to non-adopters, i.e. the share of utilities' fix-costs not covered by PV adopters [$]

To account for the market dynamics[5] of PV and BSS we include two additional metrics indicating:

a. A potential drop in the residential solar PV market, i.e. the compound annual growth rate (CAGR) in the first three years of the policy mix assessment (2016 to 2019) [%]
b. A potential uptake in the residential BSS market, i.e. the compound annual growth rate (CAGR) in the first three years in which the annual deployment of BSS at least doubles [%]

[5] From a PV and/or battery industry perspective boom and bust cycles are undesirable. While a sudden bust might lead to jobs and corporate reputation losses, a sudden uptake might create substantial spillovers if the domestic supply chain cannot supply the rapid demand growth.

Model input

The model input reflects the three most relevant policy instruments that affect the economics of residential solar PV and battery systems as outlined in Section 2. These include upfront support schemes[6] that lower the investment costs (*PI1*), retail electricity rate designs[7] that determine the composition of the electricity bill of residential customers (*PI2*), and feed-in remuneration schemes[8] that determine the level of compensation paid for PV exported to the grid (*PI3*).

Model content and logic

Spatial and temporal scales: The model has a temporal resolution of one year and extends over 26 time steps from 2005 to 2030. Spatially, California is represented through its 58 counties and 59 electric utility service areas with a resolution of 10km by 10km per grid cell. Besides the county and utility data, each grid cell is provided with specific population and irradiation data according to its location.

Agents: In addition to the roughly 12 million households in California (rescaled by a factor of 10,000), we integrate the most relevant agents affecting California's residential electricity prices. In particular, we include the regulatory agency CPUC, the three investor owned electric utility companies (comprising >80% of the market), the wholesale electricity market, as well as one technology broker. The interplay between these entities determines the impact of our three focal policy instruments on the adoption of stand-alone PV and integrated PV+battery systems, and, in turn, how the deployment affects the state's electricity market.

Process overview: Each year the model runs through three key procedures, namely (i) determining systemic electricity load and wholesale electricity prices, (ii) executing the General Rate Case to derive the retail electricity tariffs, and (iii) conducting the PV and BSS adoption process.

(i) Determining the system-wide electricity load profile and the wholesale electricity prices is done in four steps. First, all households update their net electricity load, which might have changed if they adopted PV and/or BSS in the prior year. Second, electric utilities sum up the net electricity load of all households in their service area to create their own net load. Third, the electric market entity aggregates the net load of all utilities to a system electricity load. Fourth, based on this systemic electricity load curve the wholesale electricity price is calculated.

(ii) In the General Rate Case electric utilities determine the electricity retail price for their service area. Given cost regulation, this is essentially a zero-sum game between their fixed and variable costs

[6] i.e. upfront grants and tax credits for PV and BSS
[7] i.e. type of volumetric charge (flat, time-of-use, tiered) + demand and/or fixed charges
[8] i.e. type (NEM or FIT) and level of remuneration

and the revenue they capture from their customer base via volumetric, fixed or capacity based bills, plus a fixed margin set by the regulator.

(iii) The PV and BSS adoption process is the core of the model and is implemented as a linear decision process starting with an assessment of each agent's persuasion (step 1), leading to a profitability calculation & evaluation (step 2), and eventually to the implementation of the chosen technology (step 3). Agents can stop the process at each stage of the process if they do not meet their individual cut-off criteria. In addition, particularly persuaded or aware agents leapfrog the profitability calculation and thus may implement the technologies regardless of their economic performance.

Step 1: An agent's persuasion is composed of three factors, namely personal awareness, neighbors, and general information about the technology. The three factors are combined in a weighted sum – with individual weights for each agent – and compared to a threshold. If the sum exceeds this general persuasion threshold the agent moves to step 2 and calculates the profitability of different options. If, in addition, the agent's awareness value exceeds the early-adopter awareness threshold, the agent leapfrogs the profitability calculation and directly implements the technology (step 3).

Step 2: Profitability calculation and comparison: The profitability calculation is implemented as a net present value (NPV) calculation, by which non-adopters, i.e. households possessing neither a stand-alone PV nor an integrated PV+battery system, economically assess and compare the two investment opportunities. Those households who already have a stand-alone PV system installed exclusively assess the economics of adding a BSS system to the existing installation. In case the NPV is positive, i.e. the households are economically better off than by buying electricity from the grid, the best performing option is then adopted in step 3.

Since the policy instruments included in our analysis directly affect the economics of the focal investments into stand-alone PV and integrated PV+battery systems, and by doing so unfold their impact on all of the key outputs, the economic assessment each household conducts is now introduced in detail. As introduced in Section 2, the key policy instruments include upfront support schemes that lower the investment costs (*PI1*), retail electricity rate designs that determine the composition of the electricity bill of residential customers (*PI2*), and feed-in remuneration schemes that determine the level of compensation paid for PV exported to the grid (*PI3*). Since some feed-in remuneration schemes are moderated by the going electricity rate, the latter may be regarded an input parameter of the former (*PI3*|*PI2*). Equation (1) provides an outline of how the three instruments enter the net present value calculation conducted by a residential household.

$$NPV = CAPEX(PI1) + OPEX + AvoidedCosts(PI2) + FeedInRevs(PI3|PI2) \quad (1)$$

As shown in equation (2), $PI1$ reduces the capital expenditures I_t of the focal solar PV and battery investments, either by an absolute amount in case of a grant scheme, or by a certain percentage in case of a tax credit. Both effects are captured by the scaling factors $PI1_{PV_0}$ and $PI1_{BAT_0}$ respectively (both $\in [0,1]$).

$$CAPEX(PI1) + OPEX$$
$$= I_{PV_0} \cdot PI1_{PV_0} + I_{BAT_0} \cdot PI1_{BAT_0} + \sum_{t=1}^{T} \frac{I_{BAT_t} \cdot PI1_{BAT_t} + (I_{PV_0} + I_{BAT_0}) \cdot F_{Opex}}{(1+i)^t} \quad (2)$$

Future cash flows that occur over the investment time frame of $T = 25$ years are discounted at rate i. In case the household decides to invest into a combined solar PV and battery installation, the battery needs to be replaced after 12 years. Should an upfront support scheme still be available at this point in time, the re-investment costs will be reduced according to $L1_{BAT_t}$. Operation and maintenance (O&M) costs of both the solar PV and the battery system are included as a fixed share of the initial investment costs F_{Opex} which corresponds to the assumption that O&M remain nominally stable.

$$AvoidedCost(PI2)$$
$$= \sum_{t=1}^{T} \frac{365 \cdot \left(p_{retail_t}(PI2) \times SC \times E_{PV} + p_{dcharge_t}(PI2) \cdot \max(\Delta P_{Load}) - p_{fix_t}(PI2)\right)}{(1+i)^t} \quad (3)$$

Following equation (3), several policy instruments (*PI2*) determine the avoided costs, or bill savings, that accrue to residential homeowners when investing into solar PV and battery systems. These are the going volumetric electricity rates p_{retail_t}, capacity based demand charges $p_{dcharge_t}$, and potential fixed charges p_{fix_t}. The latter follow the assumption that solar homeowners could be billed for using the electricity infrastructure predominantly as a "standby" or "backup" system. For simplicity reasons we build our annual cash flows on the average of each household's daily electricity demand and supply, which are based on hourly load and PV generation profiles. Given that the volumetric electricity costs, and thus the savings that arise from a solar PV and battery system, depend on the specific retail rate structure, we introduce each of the three terms E_{PV}, SC, and p_{retail_t} as matrices. The most simple volumetric rate structure is a flat rate remaining stable over the entire day. Accordingly, all elements in matrix (4) are identical, both along the 24 hours of the day (rows), and across all five rate blocks (columns).

$$p_{retail_t} = \begin{pmatrix} p_{Tier1(t)_1} & \cdots & p_{Tier5(t)_1} \\ \vdots & \ddots & \vdots \\ p_{Tier1(t)_{24}} & \cdots & p_{Tier5(t)_{24}} \end{pmatrix} \quad (4)$$

In case of time-of-use pricing, the retail rate may change over the course of the day, leading to different values in each row, but constant values in each column. Last but not least, in case of a tiered rate structure, the price curve follows a step function based on the households daily electricity consumption compared to an exogenously given baseline defined by the utility company. Matrix (4) allows us to incorporate up to five distinct retail price blocks (columns 1-5) capturing the situation of most Californian households.

$$SC = \begin{pmatrix} SC_{Tier1_1} & \cdots & SC_{Tier5_1} \\ \vdots & \ddots & \vdots \\ SC_{Tier1_{24}} & \cdots & SC_{Tier5_{24}} \end{pmatrix}^{-1} \quad (5)$$

Matrix (5) illustrates the level of PV electricity that is consumed onsite during each hour of the day. In the case of a tiered rate structure, our model splits up the self-consumption to gradually “walk down” the different price blocks. In case of both flat and volatile prices, only the first column of matrix (5) is assigned with self-consumption values for the corresponding hour, while the other elements are assigned with zeros.

$$E_{PV} = \begin{pmatrix} E_{PV_1} \\ \cdots \\ E_{PV_{24}} \end{pmatrix} \quad (6)$$

To arrive at the absolute avoided costs per day, for each hour of the day the former products of volumetric prices and self-consumption fractions are multiplied by the household’s solar PV production in each hour of the day provided by matrix (6).

Last but not least, the revenue stream for selling electricity into the grid is captured in equation (7). In analogy to the volumetric electricity costs outlined in (3), we employ matrices to accommodate the temporal and structural price variations that are governed by the going retail rate design ($L2$) (cf. equations (4)-(6)).

$$FeedInRevs(PI3|PI2) = \sum_{t=1}^{T} \frac{365 \cdot \left(p_{FiR_t}(PI3|PI2) \times (1 - SC) \times E_{PV}\right)}{(1+i)^t} \quad (7)$$

This setup allows us to model the impact of alternative “Net Energy Metering” (NEM) remuneration schemes, which build on the notion that households can sell their excess generation to the grid at[9], or close to, the going retail rate of electricity p_{retail_t}, which is determined by the NEM reduction factor $L3_{NEMFactor} \in [0,1]$. In addition, our formulation also allows us to model a steady compensation based on a “Feed-in Tariff” (FIT) that is decoupled from the retail electricity rate, cf. equation (8).

$$p_{FiR_t} = \begin{cases} p_{retail_t} \cdot PI3_{NEMFactor}, & if\ NEM \\ \begin{pmatrix} PI3_{FIT} & \cdots & PI3_{FIT} \\ \vdots & \ddots & \vdots \\ PI3_{FIT} & \cdots & PI3_{FIT} \end{pmatrix}, & if\ FIT \end{cases} \quad (8)$$

[9] This case is discussed as “Full Net Metering”, which corresponds to $p_{FiR_t} = p_{retail_t}$.

3.2 Model calibration

The model has been calibrated with historic PV adoption and electricity market data from California between 2005 and 2015. On the adoption level, the installed capacity of residential PV systems was matched by adjusting the persuasion weights of PV adopters (cf. Figure 2a). In addition, the historic distribution of PV systems installations in terms of their size (cf. Figure 2b) was replicated in the model by dimensioning the PV installations in way that the annual electricity generation corresponded to each household's individual annual electricity demand.

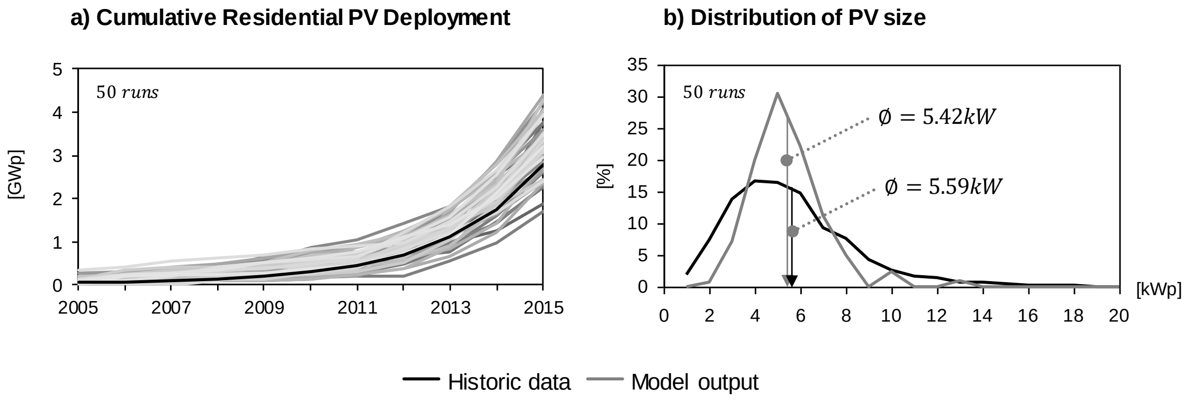

Figure 2: Model calibration; comparison of historic data (black line) and simulated data (grey line) for two key indicators, namely a) cumulative PV deployment, and b) size distribution of installed PV systems

3.3 Policy mix analysis 2016-2030

To disentangle the complex interplay of the three focal policy instruments of this study – upfront support (PI1), rate design (PI2), and FiR design (PI3) – and derive insights on how alternative mixes thereof affect the deployment of residential PV+battery systems, we employ iterative approach. In particular, based on a systematic sensitivity analysis (cf. Appendix), we have decided to use the policy mix of 2016 as a basis for a generic reference design in which all policy parameters remain unchanged until 2030. Notwithstanding such as 'Policy Freeze' (PM1) is not very realistic, it is particularly useful to illustrate the occurrence of the two system-level challenges introduced above in case no policy amendments are implemented.

This allows us to illustrate which impact the policy changes will have that are currently foreseeable, but have not yet come into effect. Therefore we study the "Current Path" (PM2) which depicts the announced changes in California's policy mix until 2022. Aggregating our insights from the sensitivity analysis and the comparison between PM1 and PM2, we then introduce one possible solution for how to address both system-level challenges simultaneously, namely the "Smart Path" (PM3). This policy mix is characterized by the introduction of a fixed charge that applies exlusively to PV+battery investors. In addition, it entails a replacement of the current feed-in remuneration via Net Metering by a Feed-in Tariff which has been widely applied in many geographies, most notably Germany (Campoccia et al., 2014; Couture et al., 2015; Kreycik et al., 2011). Based on a detailed analysis of

PM3, we derive a number of implications for policy mix design in California and beyond. An overview of the three policy mixes PM1-PM3 is provided in Table 2.

Table 2: Overview of policy mixes 2016-2030

	Name	PI1 Upfront	PI2 Volumetric	PI2 Demand Charge	PI2 Fixed Charge	PI3 Feed In
PM1	*Policy Freeze (Reference)*	ITC, SGIP at 2016 level	Tiered (3 blocks)	0$	0$	Full NEM
PM2	*Current Path*	ITC; 2020-22: phase down SGIP; 2020: instant phase out	Tiered (3 blocks) 2019: instant introduction of TOU	0$	0$	Full NEM 2019: instant phase out
PM3	*Smart Path*	ITC, SGIP at 2016 level	Tiered (3 blocks)	0$	20$/month	Feed-in Tariff 2016-2025: phase down from retail to wholesale

4 Results and Discussion

4.1 The effect of policy mixes on residential PV+battery diffusion in California

The output of the agent-based modelling of the three focal policy mixes PM1-PM3 is illustrated in Table 3. All three policy mixes lead to a similar level of cumulative PV adoption. In particular, our model estimates that by 2030 almost one quarter of all households will have installed a solar PV system. The similar level of total electricity generated from these PV systems indicates that there are only minor differences in the temporal diffusion patterns, given that earlier PV adoption leads to more electricity generated over the investigated period.

Table 3: Key results of scenario analysis

		"Policy off"	"Current Path"	"Smart Path"
	Unit	PM1	PM2	PM3
Market				
Total PV adoption	[Adopters / Ratepayers]	23%	23%	22%
PV stand-alone	[Adopters / Ratepayers]	23%	12%	11%
PV+BSS integrated	[Adopters / Ratepayers]	0%	11%	11%
Electricity Generation	[TWh total until 2030]	225.9	231.2	215.8
Market drop PV	[3year CAGR 2016/2019]	-10.5%	-10.5%	-17.9%
Market uptake BSS	[3year CAGR tail to peak]	+3.9%	+199.8%	+144.4%
NPV handshake	[Year]	-	2027	2024
Grid				
Ramping capacity	[GW/h]	1.48	1.23	1.16
Grid congestion	[m househ.]	1.82	1.34	1.17
Cross-subsidization				
Total Amount	[b US$ total until 2030]	23.81	26.41	-5.40
Feed-in remuneration	[b US$ total until 2030]	11.67	12.02	1.59
Utility fix costs	[b US$ total until 2030]	12.14	14.39	-6.99

However, there are striking differences with respect to whether these systems are deployed stand-alone, or as part of integrated PV+battery systems. Whereas PM1 appears to prohibit the uptake of battery systems, under mixes PM2 and PM3 about half of all PV systems are deployed alongside BSS. Elaborating on the drivers behind these differences, we identify the feed-in remuneration scheme (*PI3*) to be the major inhibiting factor for BSS. In particular, maintaining current Net Energy

Metering (NEM) policy until 2030 would strongly benefit the stand-alone solar PV market, but inhibit the uptake of battery storage for residential self-consumption. This finding supports the claim of advocates of residential PV+battery systems who have argued that "NEM kills storage". By contrast, since in both PM2 and PM3 the NEM policy is phased out, PV+battery becomes an attractive option for residential end consumers. In particular, for an average household, the net present value of an integrated system surpasses that of a stand-alone rooftop PV installation in 2027, and 2024 respectively. Looking at its effect on the solar PV market, we find that both PM2 and PM3 manage to avoid a crash of California's market for residential stand-alone solar PV systems, while providing a long-term perspective for the industry in the form of integrated PV+battery installations. However, a gradual decrease of the feed-in remuneration level (PM3) is likely to avoid the unintended consequences of a sudden[10] (PM2) policy change in response to system-level challenges. As shown in Figure 3a, interestingly, the BSS uptake starts even before the "NPV handshake" which may partially be explained by a neighborhood effect, i.e. early adopters of PV+battery systems attract followers even though it does not yet make sense to invest from a purely economic standpoint. What remains to be seen, however, is whether the battery storage industry would be capable to respond to the sudden ramp up of residential BSS system demand with a CAGR of 200% under PM2, and 144% under PM3, and an annual capacity deployment of about 1.5GWh/a. Given that the market for commercial, industrial, and utility-scale battery storage systems in California is already foreshadowing the development in the residential sector, and since the largest demand for batteries in 2025 is likely to come from the consumer electronics and automobile sectors, it seems reasonable to expect that the former level of demand can be met (Bloomberg, 2016).

Looking at the system-level effects of the three policy mixes (lower part of Table 3 and Figure 3b-d), we find that extrapolating the policy status quo (PM1) would entail a significant increase in the need for ramping capacity (1.5GW/h) and a significant increase in the share of households (~1.8 million) that are located in areas where solar PV feed-in exceeds 50% of the local load in 2030. When studying the underlying temporal pattern, the latter makes it likely that from 2025 onwards, upgrades of congested distribution circuits will become necessary to accommodate NEM installations. As shown in the results for PM2 and PM3 an uptake of residential BSS may significantly relax this situation. In particular, our model estimates a reduction in the amount of ramp-up capacity equivalent to one gas peaker plant (~300MW) and a decrease in the number of households in "high feed-in" areas by about 500,000 to 700,000, which concentrate around the Bay Area and the Los Angeles Metropolitan Area. Furthermore, extending the current policy mix until 2030 (PM1) would lead to a significant amount of money being shifted from end consumers without PV systems towards PV owners, both

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[10] Of course, the worst would be a retroactive policy change which happened in Spain in 2009 or Nevada in 2016 and destroyed the legitimacy of the local energy transition (Del Río and Mir-Artigues, 2012; Trabish, 2016).

in terms of feed-in remuneration (> US$ 11.6 billion) and in terms of utility fix costs (> US$ 12.1 billion).

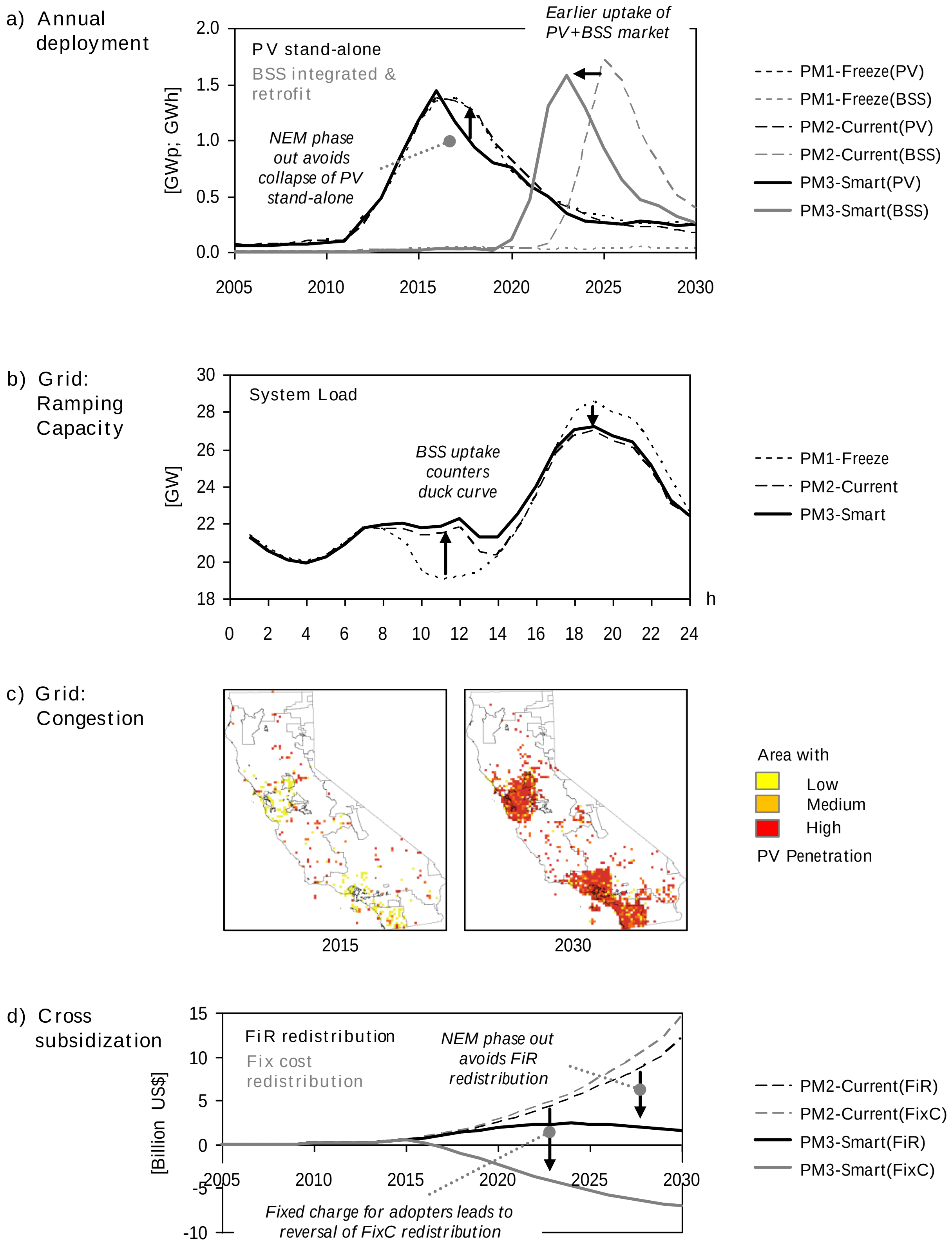

Figure 3: Key outputs for policy mixes PM1, PM2, and PM3 (if PM1 not shown, assume identical values as for PM2)

While the figures are in a similar range in case the currently foreseeable policy amendments will be implemented (PM2), the cross-subsidization issue may be significantly reduced. As shown in the results for PM3, the replacement of Net Metering through a Feed-in Tariff that gradually phases out from US$ 20 ct/kWh to US$ 2 ct/kWh over a ten-year period, would lead to a significant reduction in income redistribution between adopters and non-adopters of solar PV systems. The trend can even be reversed in the case of the shift in the utility fix costs in case of the introduction of a monthly fixed charge that only applies to adopters. However, the fact that the total amount of costs shifted from adopters to non-adopters turns out to be negative (US$ -5.40 billion until 2030) suggests that a lower fixed charge than US$ 20 per month needs to be set in order not to put an unfair burden on solar PV owners. In addition, when it comes to the implementation of such a policy mix it must be stated that, so far, no credible roadmap for the introduction of residential fixed charges has yet been announced by California's regulatory agency. Recalling the contested debates preceding regulatory decisions in the past, one may expect that such a proposal would face enormous opposition from solar PV advocates.

4.2 Insights for Theory and Practice

This study contributes to the emerging literature on policy mixes for sustainability transitions, as well as to practitioners shaping or being affected by emerging policy mixes.

First, we inform policy mix scholars about the importance of explicitly taking design features of individual policy instruments into account. The interactions between sub-aspects[11] of rate design (*PI2*) and feed-in remuneration policies (*PI3*) reveal that rather than the instrument type, the individual characteristics of policy instruments may determine how it interacts with the other elements in the policy mix. In other words, design choices in individual policy instruments may play a decisive role for the impact of the policy mix at large.

Second, this paper offers the first systematic approach and a comprehensive methodology to a) assess the impact of policy mixes ex ante, while b) quantifying the trade-offs between different policy goals, and c) endogenizing central aspects of the policy mix rather than taking it as an exogenously given, pre-determined entity. Doing so, we make an argument for complementing traditional policy design processes (muddling through) with transparent, computation-based analyses that inform policy makers about the implications of their decisions. As illustrated in this paper, agent-based modelling may aid policy makers by estimating the combined impact of multiple policy instruments along multiple goals, while taking behavioral aspects such as boundedly rational adoption processes and local adaptation into account. In addition, the key purpose of these studies may not lie in rendering directly implementable policy mixes, but rather helping decision makers understand the underlying mechanisms and the major levers at their disposal. In this regard, we raise the concern that over-

[11] Such as the composition of volumetric, demand and fixed rates (cf. Table 1)

sophisticated modelling approaches may be misleading when it comes to conducting analyses that provide value to practitioners.

Third, this paper holds valuable insights for policy makers and stakeholders of the emerging residential PV+battery domain in California. In particular, elaborating on three specific policy mixes, we add to the distinct but interrelated discussions on the future of some of the state's major policy programs namely SGIP, TOU rates, and NEM. The findings indicate that policy mixes in California will continue to have a strong impact on the diffusion of residential renewable energy systems in the near future. Since the different development trajectories have specific implications for the changes to the public infrastructure and the business model of regulated utilities, further analyses should be conducted to determine policy amendments that navigate the trade-offs between the various goals sketched in this paper.

This study concentrates on the composition of policy instruments into policy mixes. In turn, we do not conduct a comprehensive "optimization" of the policy mix, which would include optimizing the characteristics (e.g. its support level, the timing (when introduced/phased out), and the sequence (in which order) of each of the underlying policy instruments. Hence, future studies could adopt a more comprehensive approach when looking for policy designs tailored to specific contexts.

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Appendix

Sensitivity analysis of policy instruments

This section analyzes how sensitive the outcomes of the agent-based model are to changes in the key policy instruments. To do so, we conduct eight individual sensitivity analyses to elaborate on the absence of policies (S1), the impact of each policy instrument individually (S2-S4), the joint impact of two instruments (S5-S7), and the combined effect of all three policy instruments (S8). Table A.1 provides an overview of the sensitivity analyses.

Table A.1: Layout of sensitivity analyses for policy instruments PI1-PI3

	Name of Sensitivity	PI1 Upfront	PI2 Volumetric	PI2 Demand Charge	PI2 Fixed Charge	PI3 Feed In
S1	*Policy Off*	None	Flat	0$	0$	None
S2	*PI1*	2016 level	3 Tiers	0$	0$	None
S3	*PI2 Dcharge*	2016 level	3 Tiers	20$/kWp	0$	None
S4	*PI2 Fcharge*	2016 level	3 Tiers	0$	20$/month	None
PM1	*PI3 NEM (Policy Freeze; Ref)*	2016 level	3 Tiers	0$	0$	Full NEM
S5	*PI2 Dcharge, PI3 NEM*	2016 level	3 Tiers	20$/kWp	0$	Full NEM
S6	*PI2 Fcharge, PI3 NEM*	2016 level	3 Tiers	0$	20$/month	Full NEM
S7	*PI2 D+Fcharge*	2016 level	3 Tiers	20$/kWp	20$/month	None
S8	*PI2 D+Fcharge, PI3 NEM*	2016 level	3 Tiers	20$/kWp	20$/month	Full NEM

We decide to exclude policy instrument 1 (PI1), i.e. the upfront support schemes for PV and BSS, from the combinatory sensitivity analyses, because, even though they have a significant impact on the short-term market uptake of the two focal technologies, their effect diminishes over the next years since they are likely to be phased out. Hence, for simplicity reasons we fix the upfront support at 2016 levels, meaning that the ITC for PV and BSS remains at 30% and the SGIP for BSS at US$ 1.31[12] per Watt. For comprehensibility reasons, we also do not specifically assess a particular design feature of policy instrument 2 (PI2), namely the impact of different volumetric rate options. Instead, besides the "Policy Off" analysis (S1) we assume that customers continue to pay tiered[13] electricity rates, which corresponds to the current situation of most Californian households. In the presence of a tiered rate structure households who generate and consume their electricity on site face decreasing

[12] Attached to the boundary condition that 40% of the battery investment costs need to be covered by the household itself.

[13] A tiered rate structure means that electricity prices increase with higher consumption. In particular, the daily electricity is distributed into different consumption tiers determined based on an exogenously given baseline. Hence the electricity price is a weighted average of the consumption in each tier.

marginal returns for every additional kWh they produce. The reasons is that the marginal bill savings decrease the lower the initial tier level of a given household.

Table A.2: Key results of scenario analysis

		Policy off	PI1 UG	PI2 DC	PI2 FC	PI3 NEM	PI2/3 DC/NEM	PI2/3 FC/NEM	PI2 DC/FC	PI2/3 D/F/NEM
	Unit	S1	S2	S3	S4	PM1	S5	S6	S7	S8
Market										
Total PV adoption	[Adopters / Ratepayers]	22%	23%	22%	22%	23%	23%	23%	21%	22%
PV stand-alone	[Adopters / Ratepayers]	12%	12%	11%	11%	23%	20%	22%	12%	19%
PV+BSS integrated	[Adopters / Ratepayers]	10%	11%	11%	11%	0%	3%	1%	9%	3%
Electricity Generation	[TWh total until 2030]	155.3	207.9	188.8	178.7	225.9	213.1	215.1	164.4	189.9
NPV handshake	[Year]	2021	2021	2021	2021	-	-	-	2022	-
Grid										
Ramping capacity	[GW/h]	1.14	1.18	1.16	1.15	1.48	1.44	1.46	1.14	1.39
Grid congestion	[m househ.]	1.14	1.26	1.23	1.19	1.82	1.71	1.78	1.12	1.57
Fairness										
Total Amount	[b US$ total until 2030]	11.23	14.79	11.24	-4.67	23.81	17.82	0.89	-6.10	-3.18
Feed-in remun.	[b US$ total until 2030]	0.41	0.43	0.40	0.42	11.67	8.87	10.65	0.43	7.4
Utility fix costs	[b US$ total until 2030]	10.82	14.34	10.84	-5.09	12.14	8.94	-9.76	-6.53	-10.57

The aggregated outcome of the sensitivity analysis are provided in Table A.2, while the annual diffusion figures of the reference case PM1 and the individual sensitivities of the policy measures that are most prominently discussed in California (S2-S4, based on instruments PI2 and PI3) are illustrated in Figure A.1.

The outcome of S1 reveals that a direct phase out of all upfront, rate design, and feed-in remuneration policies would entail an immediate collapse[14] of the stand-alone solar PV market. At the same time we also find that the deployment eventually recovers, namely once the combined PV+battery systems become economically attractive for an increasing number of residential homeowners. In other words, S1 reveals that residential PV+battery systems diffuse even in the absence of direct policy support, however with much less PV electricity being produced in the observed time period which is caused to

[14] Since our focus lies on PM1 and S2-S4, the figures are not explicitly illustrated.

the late recovery of PV+battery systems after the initial bust of the stand-alone solar PV market. Moreover, while the immediate end of the Net Metering (NEM) program would curtail the redistribution effect stemming from the feed-in remuneration for PV adopters to a total amount of US$ 409 million, this would not solve the issue of cross-subsidization because of the redistribution of fix costs (exceeding US$ 10.8 billion) from adopters to non-adopters. This is because the costs for operating the infrastructure remain included as part of the volumetric electricity rates.

Whereas section 4 discusses the reference case PM1 in detail, in the following we will concentrate on the analysis of S2-S8. Policy mix S2 reveals that in case of an instantaneous NEM phase out, the market for residential stand-alone solar PV systems would collapse, dropping by about 64% in one year. As a result of the increased attractiveness of onsite consumption compared to feeding PV electricity into the grid, integrated PV and battery storage systems start to gain attention, reaching NPV parity with stand-alone systems by 2021 and a total deployment of 11% of the ratepayers by 2030.

S3 shows that in case of the direct introduction of a demand charge[15] at the level of US$ 20 per kilowatt, we find that the stand-alone PV deployment would also drop by about 50% in one year. The reason is that the volumetric part of households' electricity bills is proportionally reduced to the level of the demand charge. This, in turn, decreases the profitability of investments into PV or PV+battery systems because of lower avoided costs. However, demand charges help to reduce the amount of utility fix cost that non-adopters need to be cover. As observed before, under the presence of NEM we see no significant deployment of integrated PV+battery systems.

S4 indicates that when introducing a fixed charge at the level of US$ 20 per month, which only applies to adopters of PV and BSS the issue of cross-subsidization between customer segments almost disappears. Despite a temporal solar PV market drop, in sum the entire – even the historic – remuneration amount that is paid under the NEM scheme can be recovered. However, this rests on the assumption that the fixed charge revenues collected by utilities are directly used to cover their fix costs, and thereby contribute to lower the volumetric charges for all residential customers. In other words, fixed charges can be regarded an effective counter-measure against cross-subsidization. Once again, given the presence of NEM in S5, virtually no uptake of integrated PV+battery systems does occur.

[15] Based on the peak demand during a pre-defined system peak hour intervall.

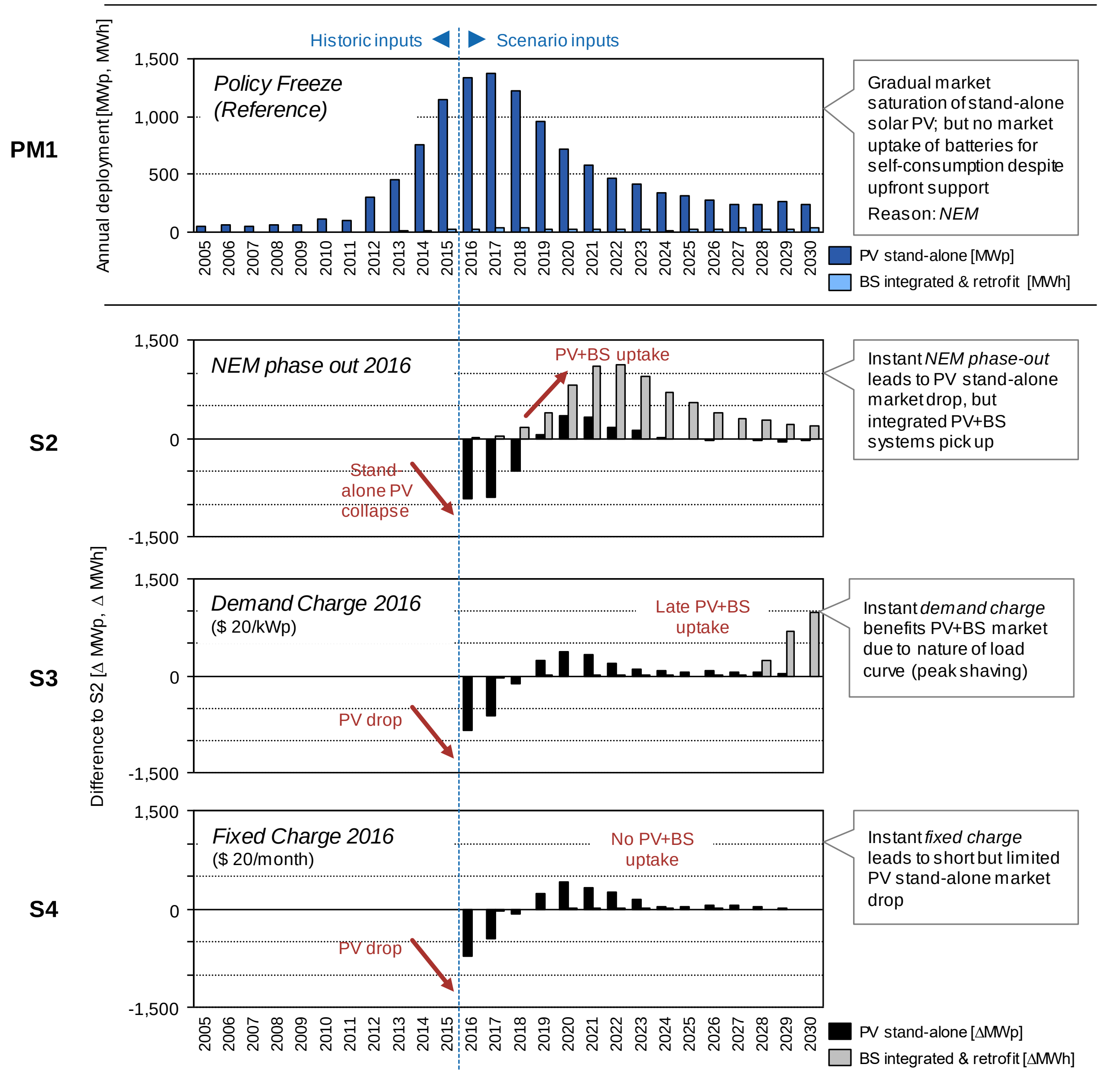

Figure A.1: Sensitivity of residential PV+battery deployment to key policies
Reference policy mix: PM1 – Policy freeze (Upfront Grants 2016, 3 Tiers, Full NEM)

Assessing the combined impact of the aforementioned policy instruments, we find that the results are mostly in line with the expectation based on the individual effects. In particular, we find that when pairing an immediate NEM program exit with a demand charge (S5) or a fixed charge (S6), both lead to a collapse in the stand-alone solar PV market and a surge in the integrated PV+battery market around 2021. Last but not least, the combinations of demand and fixed charges (S7), and all three policy options (S8) both confirm our previous findings, while the former is characterized by the largest amount being redistributed from adopters to non-adopters (US$ -6.10 billion).