Solar and Wind Deployment: A Comparison of Experiences in Germany, California and Texas

Facts and Brief Analysis

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ABSTRACT

In light of progressing climate change, both Germany as well as the two U.S. federal states California and Texas have enacted decarbonization strategies based on renewable energies. At the same time, the policy instruments to pursue their goals differ substantially. This comparative study identifies similarities and differences in policy structures as well as the penetration of variable renewable resources. It shows a fast deployment of wind and solar power in Germany at comparatively high cost. At the same time, it reveals that the two U.S. markets could ameliorate the investment conditions for renewable energy via three measures: 1. Reduction of institutional obstacles and transaction costs, 2. Introduction of CO2-pricing (Texas) or increasing CO2-pricing (California), 3. additional support schemes for wind and solar, if substantive reasons for additional support prevail.

Keywords: Comparative analysis, Decarbonization, RES deployment, Energy sector regulation

JEL classification: Q42, Q48, L94, N70

PROJECT DESCRIPTION & ACKNOWLEDGEMENTS

Germany as well as the U.S. states of California and Texas have enacted policies and implemented programs to incentivize the expansion of renewable generation in electricity systems. Each of these markets vary with respect to the capacity installed, the costs to ratepayers and the impacts on incumbent utilities and conventional generators. Germany, California and Texas provide important – and in some aspects contrasting – examples of how policies can be put into effect as well as the potential of renewable deployment and the impact of increased renewable penetration on the market.

Within this research project, the expansion of renewables in Germany, California and Texas is analyzed to identify similarities and differences in policy structures as well as the penetration of variable renewable resources. In doing so, the state of renewable energy in Germany, California and Texas is examined via three independent case studies. Two additional studies compare the differences and similarities between these three markets.[1]

The document at hand compares the differences and similarities of solar and wind deployment in Germany, California and Texas.

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[1] The case study on Germany was published by EWI [5]. The other comparative study on Germany, California and Texas was published by Steyer-Taylor Center for Energy Policy and Finance, Stanford University: https://law.stanford.edu/publications/a-tale-of-three-markets/

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ABBREVIATIONS

BDEW	Federal Association of Energy and Water Industry (“Bundesverband der Energie- und Wasserwirtschaft“)
BMWi	Federal Ministry for Economic Affairs & Energy ("Bundesministerium für Wirtschaft und Energie")
BnetzA	Federal Network Agency ("Bundesnetzagentur")
CA	California
CAISO	California Independent System Operator
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CPUC	California Public Utilities Commission
CSI	California Solar Initiative Program
CSP	Concentrated solar power
DE	Germany
Destatis	Federal Statistical Office
DSO	Distribution system operator
ECB	European Central Bank
EEG	Renewable Energy Source Act ("Erneuerbare-Energien-Gesetz")
EEX	European Energy Exchange
EIA	U.S. Energy Information Administration
ELCC	Effective Load Carrying Capability
ENTSO-E	European Network of Transmission System Operators for Electricity
EPEX SPOT	European Power Exchange
ERCOT	Electric Reliability Council of Texas
EU	European Union
EU-ETS	European Union Emissions Trading System
FERC	U.S. Federal Energy Regulatory Commission
FIT	Feed-in tariff
GHI	Global horizontal irradiance
GHG	Greenhouse gas

GW	Gigawatt
GWh	Gigawatt-hour
ICE	Intercontinental Exchange
ISO	Independent system operator
km^2	Square kilometer
kWh	Kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LCOE	Levelized cost of energy
m/s	Meters per second
m^2	Square meter
MW	Megawatt
MWh	Megawatt-hour
NREAP	National Renewable Energy Action Plan
NREL	U.S. National Renewable Energy Laboratory
OECD	Organisation for Economic Co-operation and Development
OTC	Over-the-counter
PG&E	Pacific Gas & Electric Co.
PTC	Production tax credit
PV	Photovoltaics
RAM	Renewable auction mechanism
RE	Renewable energy
REC	Renewable energy credit
ReMAT	Renewable market adjusting tariff
RPS	Renewable portfolio standard
SAIDI	System Average Interruption Duration Index
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
SGIP	Self Generation Incentive Program
tCO_2	Ton of CO_2
TSO	Transmission system operator

TWh	Terawatt-hour
TX	Texas
UBA	Federal Environment Agency ("Umweltbundesamt")
VRE	Variable renewable energy (e.g. wind and solar)

1 INTRODUCTION AND ELECTRICITY MARKETS OVERVIEW

In light of the challenge to tackle climate change, Germany and the two U.S. states California and Texas pursue decarbonization strategies in parts based on carbon-neutral renewable electricity generation. They have enacted policies and implemented programs to incentivize the deployment of renewable electricity generation, with varying results. The three electricity markets provide important and in some aspects contrasting examples of how policies balance and reconcile the goals and interests of society and diverse industry participants.

This comparative study sheds light on the three market designs, identifies key similarities and differences of the three markets and suggests some implications for future renewable energy ("RE") deployment.

Due to data availability restrictions for the two U.S. markets, this report both features data on a state level (California and Texas) as well as data on a system operator level (California Independent System Operator/"CAISO", and Electric Reliability Council of Texas/"ERCOT").

Electricity Markets Overview

The three electricity markets under consideration vary in terms of area, customers and customer density. While the estimated areas of CAISO and the German electricity market are in a similar range (CAISO: 323´000 km^2, Germany: 357´000 km^2), their area spans only about two thirds of the estimated ERCOT area (ERCOT: 522´000 km^2) (Table 1).[2] In terms of number of customers, the two U.S. markets are in a similar range: CAISO serves around 30 million customers and ERCOT around 24 million customers: In contrast, the German electricity market comprises around 81 million customers. In consequence, the customer density also varies considerably. While in CAISO there are about 83 customers per square kilometer on average, the customer density in ERCOT is about half of that with 46 customers/km^2. In contrast, at 227 customers/km^2 Germany's customer density is almost five times higher than ERCOT and well above double the customer density of CAISO.

	CAISO	ERCOT	DE
Area (est.) [km^2]	360´000	522´000	357´000
Customers [Mio]	30	24	81
Customers / km^2	83	46	227

Table 1, data provided by DESTATIS [1], CAISO [2], ERCOT [3] and the U.S. Census Bureau [4]

Electricity markets consist of four main players: Generators (electricity generation), grid operators (electricity transmission), utilities (retail of electricity), and, at least in liberalized markets, flexible consumers. As a consequence of the liberalization of electricity markets, the transmission grid and electricity generation are unbundled in all three markets, yet in each market to a different degree. In the two U.S. markets, liberalization resulted in the founding of independent system operators ("ISO") (namely CAISO and ERCOT) to govern the transmission system, to serve as a trading platform for the

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[2] The service areas of CAISO and ERCOT were estimated based on information on their respective websites.

wholesale electricity market and to organize electricity dispatch.[3] In Germany, liberalization led to the creation of the transmission system operators ("TSOs") and a liberalized wholesale market. The former operate the transmission system and are responsible for re-dispatch[4], whereas the latter serves as trading platform for the wholesale electricity market and plays an important role in the dispatch.

Bidding zones

The CAISO electric region is divided into three different bidding zones for the wholesale market and the ERCOT area is split into four bidding zones (known as "trading hubs"). In contrast, only one bidding zone exists in Germany (and includes Austria).

ISOs, TSOs and Electricity Trading

The CAISO is responsible for operating the day-ahead, hour-ahead and real-time markets. Most electricity in the CAISO electric region is traded on these three markets. In contrast, the largest part of ERCOT's load is served through bilateral contracts between utilities and generators. The remainder is traded on the spot market through a centralized balancing market to ensure that generation and load is balanced in real time. Ancillary services are provided by ERCOT, but market participants can also choose to provide ancillary services themselves. In Germany, electricity is traded bilaterally (over the counter – OTC) or on the power exchange. The largest share of financial electricity trading volume is made as OTC trades (around 93%), whereas around 7% are traded on the electricity exchange. On the derivatives exchange (European Energy Exchange, "EEX"), power contracts (either weekly, monthly, quarterly or yearly) are traded, with a lead time of at least one week. Short-term contracts for physical delivery are traded on the day-ahead or the intraday market, organized by the European spot exchange (European Power Exchange, "EPEX SPOT"). Furthermore, products for ancillary services are traded on a separate balancing power reserve market. Ancillary service products are procured by the TSOs.

In the CAISO electric region, the ISO manages the central dispatch of power plants by taking congestions and thereby transmission costs into account. The day-ahead market opens seven days in advance and closes at 10 a.m. the day before delivery, during which period market participants submit supply offers and demand bids, prices are cleared and transactions are settled. Typically, utilities are the buyers and generators are the sellers. CAISO also considers hour-ahead schedules for imports and exports. It simultaneously analyzes the ancillary services market along with the electricity market to account for congestion management. The real-time market, a spot market, opens once the day-ahead process is complete and is responsible for procuring electricity and managing real-time congestion. To balance generation and load, CAISO can re-dispatch resources every five minutes. In the ERCOT market, the day before delivery, market participants have to submit their generation schedules to ERCOT.

In contrast to California, the dispatch in Germany is not managed by the TSOs. In general, the power plant operators are responsible for the dispatch, and – due to the single bidding zone applied to

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[3] Dispatch indicates the schedule for power plant utilization [5].
[4] Re-dispatch describes the short-term changes in the dispatch on order by the TSOs to address congestions [5].

Germany - they do not take grid congestions into account. The power plant operators announce the timetable for power plant operation to their respective TSO on the day before delivery (so-called ”nomination”). The cumulative schedules of all control areas yield the German dispatch for the next day, which is then analyzed by the TSOs. If network congestions are foreseen to occur, then re-dispatch measures are applied by the TSOs. On the intraday market short-term trades are made, e.g. to manage deviations from load, RE forecast or to account for power plant outages. Furthermore, reserve power is used to maintain system stability.

Generation and Retail of Electricity

In California, electricity generation and the retail of electricity within the CAISO electric region is controlled by the CAISO, i.e., a generator cannot independently sell to utilities and utilities cannot generate and sell their own electricity without the CAISO intervening. In contrast, in ERCOT and Germany, there exist integrated companies that both own power plants and also take part in retail business, albeit in different business units which have to observe legal unbundling obligations. Texas and Germany have opted for retail competition and, in turn, retail prices are not regulated. In California, retail competition does not exist and hence retail prices must be regulated. The California Public Utilities Commission (“CPUC”) possesses full authority over the utilities including managing the operations, design and setting of retail prices.

Grid

In Germany, three of the four TSOs are ownership unbundled while one TSO is legally unbundled. With respect to the distribution grid in Germany, many distribution system operators, in particular small ones, are still fully vertically integrated with local utilities. In Texas, business activities of the transmission and distribution utilities are requested to be separated from power generation and retail activities [6]. In California, most of the network is owned by investor-owned utilities, which are allowed to simultaneously own generation facilities. However, both in California and Texas, the transmission grid is operated by the independent system operators (CAISO and ERCOT). Thus the ISOs are responsible for transmission network operation, but do not own the network [7].

Interconnection with neighboring states / countries

ERCOT can be characterized as an “intra-state” market with little interconnection to other U.S. markets (1.1 GW total capacity or 2% of peak demand, consisting of two DC links with a total capacity of 820 MW to the Eastern Interconnection and three DC links with a total capacity of 286 MW to Mexico). The CAISO, on the other hand, is a member of the Western Electricity Coordinating Council, which ensures reliability throughout the entire Western Interconnection. The Western Interconnection stretches longitudinally from Canada to Mexico and includes states as far as Colorado. Total import capacity for CAISO exceeds 10 GW or roughly a fifth of peak demand. Germany is part of the European Internal Market for Electricity. It is interconnected with neighboring countries including Sweden, Denmark, Poland, the Netherlands, Luxemburg, France, the Czech Republic, Switzerland and Austria. The total average net transfer capacity was slightly below 22 GW in 2012, which corresponds to roughly a quarter of German peak demand.

2 SIMILARITIES AND DIFFERENCES

2.1 Wind and PV in the Power Plant Portfolio

While the generation shares of wind were in a roughly similar range for California, ERCOT and Germany in 2014, the installed capacities and generated energy vary due to the different market sizes and natural resource qualities. For Photovoltaics ("PV"), only Germany has developed substantial capacities, which however, do not translate into equivalent generation shares due to the rather poor quality of the German solar resource.

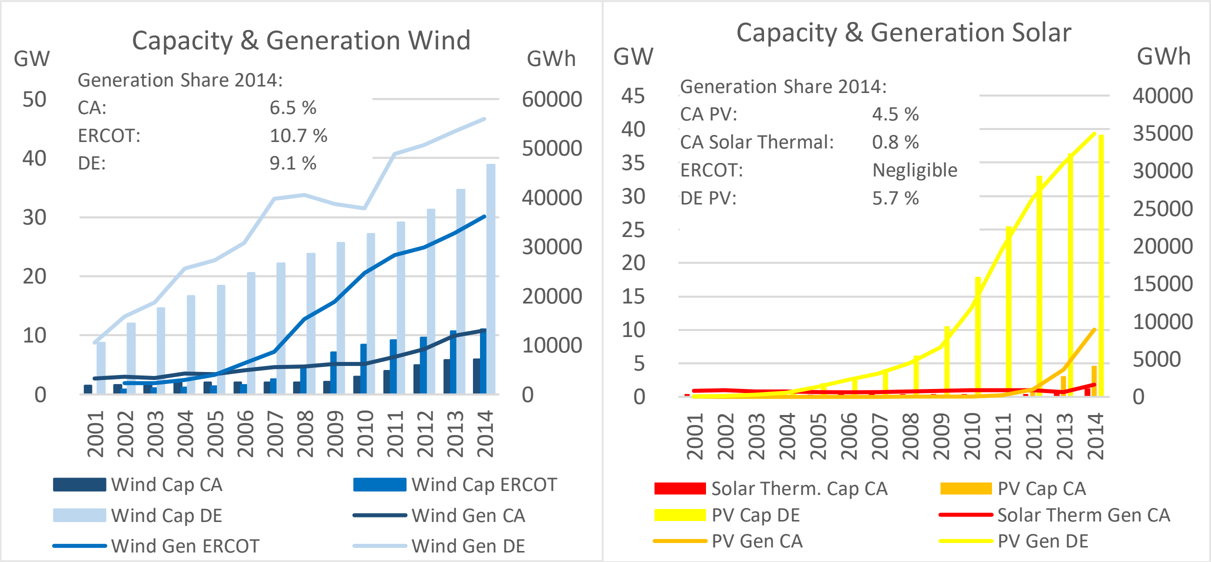

Figure 1, Source: EWI, data provided by BMWi [8], BNetzA [9], California Energy Commission [10], ERCOT [11] and Stanford

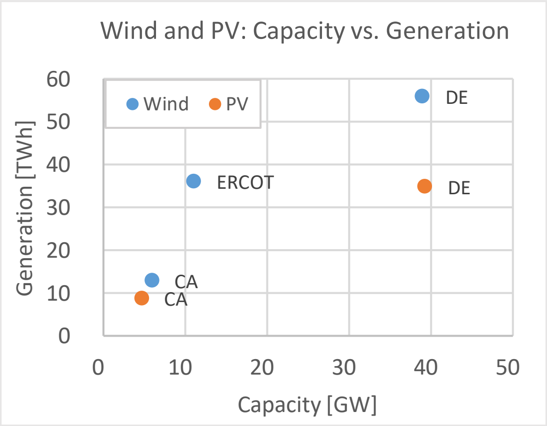

Figure 2, Source: EWI, data provided by BMWi [8], BNetzA [9], California Energy Commission [10], ERCOT [11] and Stanford

The amount of installed wind capacity has strongly increased over the last decade, with annual growth rates of <1%-38% in California, 5%-67% in ERCOT and 6%-14% in Germany. In 2014, the installed wind capacity in Germany was about three times higher than in ERCOT and more than 6 times higher compared to California (California 6 GW, ERCOT 12 GW, Germany 39 GW) (Figure 1). The generation was equal to around 13´000 GWh, 36´100 GWh and 56´000 GWh in California, ERCOT and Germany, respectively. This translates to shares of 6.5%, 10.1% and 9.1% of total generation.

While in Texas there was a total installed PV capacity of 330 MW in 2014 (with 129 MW installed in 2014, translating into an annual growth rate of 64%)[5], the installed PV capacity in California increased from 0.1 GW in 2010 to 4.6 GW in 2014 with annual growth rates of 50%-319% [12][13]. Germany saw a large increase in installed PV capacity, starting at around 2GW in 2005, rising to 18GW in 2010 and ending at just below 39 GW in 2014. Annual growth rates range from 6%-154%. In 2014, generation was around 8´930 GWh in California and around 34´900 GWh in Germany, translating to a generation share of 4.5% in California and 5.7% in Germany. Among the three markets only California contains a sizeable share of solar thermal electricity generation from concentrated solar power ("CSP"). Solar thermal capacity in California started at 0.4 GW in 2001 and rose up to 1.3 GW in 2014. The solar thermal electricity generation amounted to 1´620 GWh in 2014 which translates into a generation share of 0.8%.

A comparison of the relation of installed capacity and generated electricity for wind and PV shows that in California and ERCOT, every GW of installed capacity yields a larger contribution in terms of electricity generation than in Germany, due to the higher natural resource quality (Figure 2).[6]

The size of the three markets varies: In 2014, the total installed capacity in California, ERCOT and Germany were about 79 GW, 83 GW and 191 GW respectively (Figure 3). Total generation amounted in 2014 to 199 TWh, 339 TWh and 614 TWh, respectively. In this same year, the gross electricity demand[7] in each of the three markets reached 259 TWh in California, 340 TWh in ERCOT and 579 TWh in Germany. In California and ERCOT there were net imports of 85.6 TWh and 1.2 TWh, respectively, translating into shares of 33% and 0.3% of gross electricity demand. In contrast, in Germany there were net exports of 35.7 TWh, which accounts for a share of 6% of gross electricity demand.

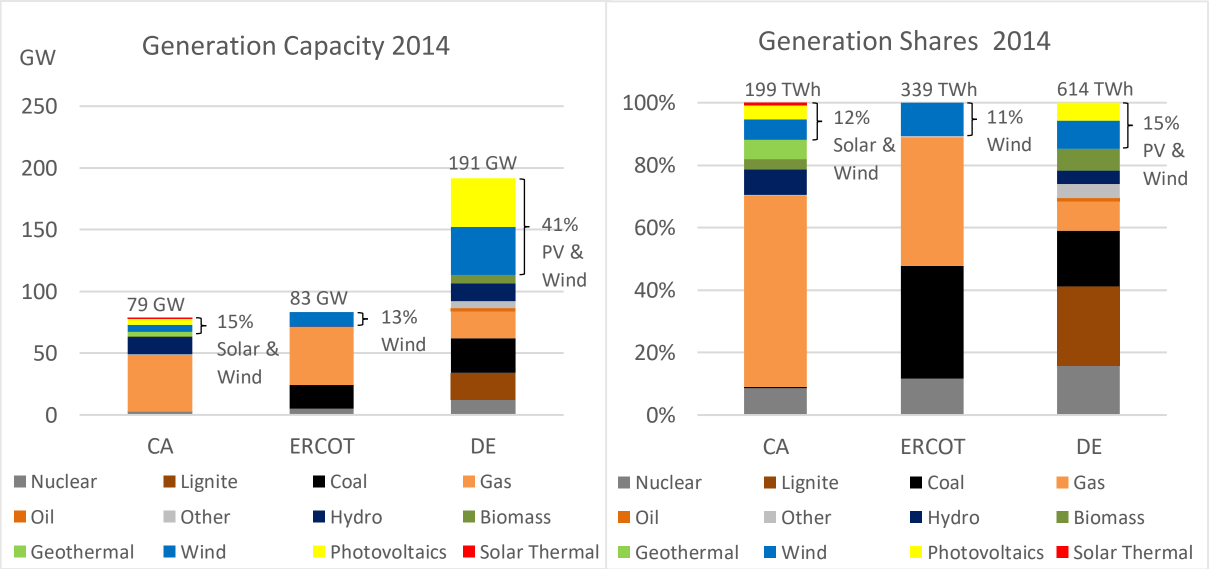

Figure 3, Source: EWI, data provided by BMWi [8], BNetzA [9], California Energy Commission [10], ERCOT [11] and Stanford

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[5] Due to the small amount of PV capacity installed in Texas, it is omitted for the remainder of this report or contained in the category "other" with regard to capacity and generation data. However, PV has a great potential in Texas and the market is gaining momentum with 6´500 MW of solar projects under review by ERCOT for grid interconnection [12].

[6] For a more detailed discussion, see Section 2.2.

[7] Gross electricity demand is defined as total generation plus imports minus exports.

Except for the low, but positive share of nuclear in all of the three markets, their generation mix shows some important differences. While in California and ERCOT gas-fired power plants have the largest share of both installed capacity and generation (California: gas capacity = 48 GW/gas share of generation = 61%, ERCOT 48 GW/41%), they play a much less important role in Germany (Germany 27 GW/11%). In contrast to California and ERCOT, lignite power plants in Germany make up a comparably large share of installed capacity (21 GW) as well as generation (26%). Coal plays only a minor role in California, in contrast to ERCOT and Germany, where it accounts for significant shares in capacity and generation (ERCOT 18 GW/37%, Germany 27 GW/20%).

Capacity Factors / normalized Full Load Hours

A measure for the average capacity utilization is given by the capacity factor indicating how much electricity a generator actually produces relative to the maximum it could produce at continuous full power operation during the same period.[8] With marginal generation costs close to zero, Wind and PV are likely to be among the first technologies in the merit-order, irrespective of whether they are granted priority dispatch. Given non-negative prices, i.e. as long as there is demand to absorb the electricity generated, and no grid congestions, wind and PV thus will always produce when natural resources are available.[9] Thereby, in case curtailments are negligible, the capacity factor of PV and wind power plants can be interpreted as their average generation availability for a specific year with its specific resource availability. In 2014, the capacity factor of PV in California was about more than twice the one in Germany, equal to about 26% in California and 11% in Germany (Figure 4). The

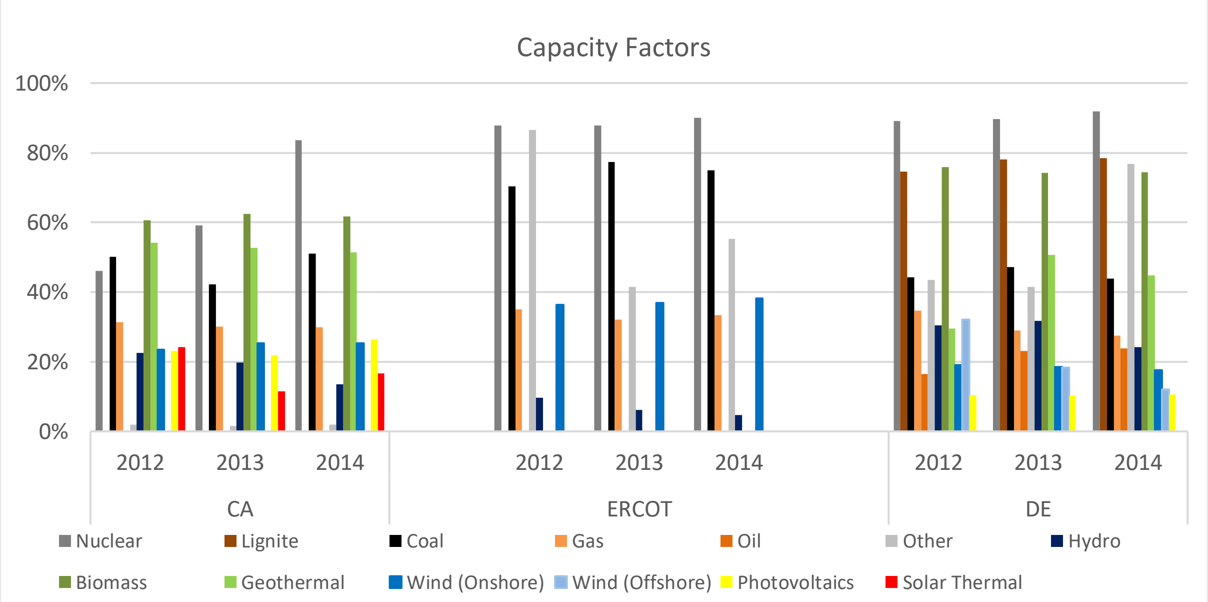

Figure 4, Source: EWI, data provided by BMWi [8][15], BNetzA [9], California Energy Commission [10], ERCOT [11] and Stanford

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[8] The yearly capacity factor is given by the quotient of total yearly generation divided by the product of total installed capacity times total hours of the year. It indicates how much electricity a generator actually produces relative to the maximum it could produce at continuous full power operation during the same period [14].

[9] Under the current remuneration scheme in Germany (FIT and Market Premium), variable RE have an incentive to generate at negative market prices, as long as the sum of negative market price and remuneration is still positive. However, remuneration for hours with negative prices is cancelled if market prices have been negative for more than 6 hours in a row. This regulation incentivizes a flexibilization of the conventional power plant park.

capacity factor of wind onshore was highest in ERCOT, featuring a capacity factor of about 38% in ERCOT, 25% in California and about 18% in Germany for the years considered. It is important to bear in mind that the capacity factor of wind and PV depends on the resource quality in the respective year, the efficiency of the installed wind and PV capacity, curtailments as well as the average resource quality of locations where Variable renewable energy ("VRE") capacity is installed.

The specific greenhouse gas emissions per GWh of total net electricity generation yield an estimate of how much of the electricity sector has been decarbonized. As this analysis gives an estimate of the specific emissions of in-state generated electricity, exports and imports of electricity distort this area-specific analysis which does not take into account system interconnections. Net imports account for around 33% of gross electricity demand in California, net exports account for around 6% in Germany and in Texas, imports are negligible. Thus, for simplification, in this analysis only for California two values for the specific CO_2-emissions are stated: one with and one without imports.

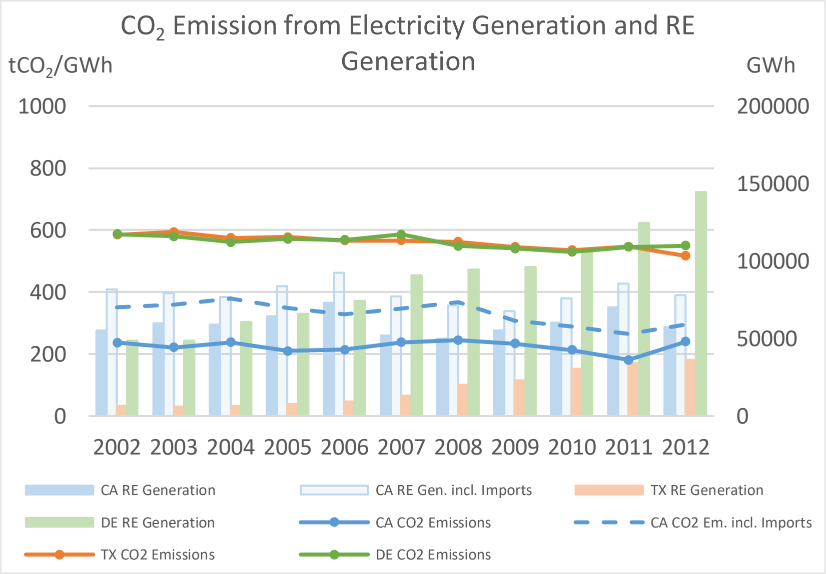

Figure 5, Source: EWI, data provided by BMWi [8], California Energy Commission [17], EIA [18] and Stanford

Texas featured a RE share of roughly 8% of total generation and large shares of coal and natural gas in 2012. The CO_2-intensity of its generation mix is thus naturally high, being at around 520 tCO_2/GWh in 2012 (Figure 5). The German power plant mix was at around 550 tCO_2/GWh in 2012 - despite a RE share in total generation of 24%.[10] This can be explained by the high generation share of carbon-intensive lignite (26%) as well as coal (18%). California featured a CO_2-intensity of around 240 tCO_2/GWh[11] in 2012, which can be attributed to its power plant mix without coal or lignite, consisting of zero-carbon RE technologies, nuclear and comparably low-carbon natural gas. If imports are considered, California´s CO_2-intensity was at 295 tCO_2/GWh. In California, one sees a close link between RE generation and CO_2-intensity. A reduction in hydro generation in 2012 led, amongst others, to a complementary increase in CO_2 emissions from 2011 to 2012. Also in Texas, the increase in RE generation led to a decrease in CO_2 emissions. In Germany, however, the so-called "Energiewende-Paradoxon" took place: Despite a strong increase in zero-carbon RE generation, the CO_2 emissions slightly rose from 2010-2012. This can be explained by a combination of factors: The immediate shut-down of 8 GW nuclear capacity in the aftermath of the

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[10] UBA states slightly different specific CO2 emissions because they use net electricity consumption as a reference [16]. For comparability reasons, in this report, net electricity generation was used to calculate the specific CO2 emissions as no net electricity consumption data were available for California and Texas.

[11] GHG-emissions of imports not considered.

nuclear disaster in Fukushima-Daiichi led to an increase in more carbon-intensive generation, at the existing fuel an CO_2 prices mostly lignite and hard coal. Also, electricity exports increased during those years, being based both on the rise in lignite generation as well as VRE generation. Thus, despite the displacement of mostly natural gas generation by RE generation, the rise in fossil, mostly coal-fired generation overcompensated the CO_2 emission reduction by VRE. Moreover, in the EU, the positive effect on CO_2 emissions by VRE is compensated by CO_2 emissions elsewhere, since the EU emission trading system caps total emissions in the EU without regard for their location within the EU.

2.2 Natural Resource Quality & Technology

Photovoltaic power plants (PV)

The natural resource quality varies in the three markets. Solar irradiance is considerably higher in California and Texas which suggests that there should be a better case for PV in those markets compared to Germany.

Solar Irradiance (GHI)			
kWh/m^2/year	CA	TX	DE
Min	1´391	1´632	951
Max	2´190	2´154	1´257
Average	1´920	1´840	1´055
LCOE PV, 2014			
cents USD_{2014}/kWh	CA[12]	TX	DE[13]
Min	7.90	9.00	10.45
Max	1.68	18.60	19.03

Table 2, data provided by Fraunhofer ISE [20] and Lazard [21]

The average global annual solar irradiance on a horizontal surface ("GHI") in California ranges from 1´391-2´190 kWh/m^2, with an average of 1´920 kWh/m^2 (Table 2). In Texas, the GHI ranges from 1´632-2´154 kWh/m^2, with an average of 1´840 kWh/m^2, while in Germany the GHI is much smaller and ranges from 951-1´257 kWh/m^2, with an average of 1´055 kWh/m^2.

In Germany, more than two thirds of PV capacity (68%) consist of rooftop systems with an installed capacity < 1 MW while about one third are larger, ground-mounted PV plants. In California, in 2013, only a small share of total installed PV capacity (2%) had a nameplate capacity of < 1 MW while 98% of PV plants were utility-scale plants with a capacity > 1 MW. In Texas, at least 64% had a nameplate capacity > 1MW.[14] In comparison, both U.S. markets feature more utility scale projects while in Germany residential rooftop systems have make a big share of total installed capacity.

It seems reasonable to expect that higher generation due to better natural resource quality should translate into lower cost of electricity generation from PV power plants. However, a comparison of the levelized cost of electricity ("LCOE"[15]) shows that PV cost are in a similar range. LCOE for PV in California range from around 7.9 to 16.8 cents USD_{2014}/kWh (Table 2). In Texas, LCOE spanned 9.0-18.6 cents USD_{2014}/kWh, while Germany saw a similar range of around 10.5-19 cents USD_{2014}/kWh. A comparative study on residential PV prices in Germany and U.S. by the Lawrence Berkeley National Laboratory

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[12] As California data were not stated separately, data for "southwestern U.S." were taken.

[13] DE: LCOE data for 2013. LCOE data 2014 for Germany were not yet available.

[14] No detailed data available, approximated from EIA data and Texas Solar Power Association [19][12].

[15] LCOE is calculated by summing all plant-level costs (investments, fuel, emissions, operation and maintenance etc.) and dividing them by the amount of electricity the plant produced in its lifetime.

identified multiple market drivers for the apparent cost advantage for PV in Germany, including generally lower non-hardware costs, one contiguous market, one regulatory framework and higher population density, less onerous permitting-inspection-interconnection processes, lower installation times, lower customer acquisition and overhead cost, and regularly stronger competition among installers [22].[16]

Interestingly, to date, ERCOT has seen almost no PV capacity deployment despite of the quality of its resource and the peak demand coincidence, especially relative to Germany. Also in sunny California, the share of installed PV capacity with respect to peak demand accounted to only about one fifth as compared to Germany (CA: 10%, DE: 49%). With anticipated maturing of the PV installation market and simplification of bureaucratic burdens, however, there could be a case for stronger deployment of PV in California and Texas in the future.

Onshore wind power plants

A comparison of capacity factors of wind power plants (see Section 2.1) suggests that also for onshore wind power, average conditions are better in ERCOT and CAISO as compared to Germany. However, this analysis requires further research, as other factors such as efficiency of installed technology and natural resource quality fluctuations for different years also influence the capacity factors and need to be analyzed.

Wind Speeds (at 80m above ground)			
m/s	CA	TX	DE
Min	4	5	3.7
Max	10	10	7.9
LCOE Wind Onshore, 2014			
centsUSD$_{2014}$/kWh	CA[17]	TX	DE[18]
Min	5.50	4.30	6.03
Max	8.10	6.10	14.34

Table 3, data provided by Fraunhofer ISE [20] and Lazard [21]

Typical onshore wind locations in California feature wind speeds at 80m above ground of 4-10 m/s, in Texas they range from 5-10 m/s, while in Germany, generators see wind speed of 3.7-7.9 m/s (Table 3).

For wind onshore, LCOE in California ranged from 5.5-8.1 cents USD$_{2014}$/kWh, in Texas from 4.3-6.1 cents USD$_{2014}$/kWh and in Germany from around 6 at the very best locations to 14.4 cents USD$_{2014}$/kWh (Table 3). In particular the upper limit of LCOE tends to be lower in California and Texas. Given the higher capacity factors in CAISO and ERCOT, it is likely that there is substantial wind energy potential in these regions at LCOE which lower as compared to Germany. However, this thesis needs to be quantified by further research.

System-friendly wind and PV deployment

In the recent years, in Germany, the debate came up whether at high shares of wind and PV, more focus should be laid in a system-friendly RE deployment. Location, technology mix and economic

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[16] Real prices labeled USD$_{2014}$ has been calculated for all price data in this report using ECB exchange rates [23] and OECD consumer prices [24].

[17] As California data were not stated separately, data for "U.S. Southwest" were taken.

[18] DE: LCOE data for 2013. LCOE data 2014 for Germany were not yet available.

design specifications can play an important role in this respect. From a system cost perspective, cost-effectiveness is not just about deploying the cheapest technology or deploying where resources are best: Also, the mix of PV, wind and dispatchable generation[19] can be optimized. In addition, by using diversification effects from the siting of wind and PV power plants, aggregate variability can be reduced and/or costs for grid connection can be lowered. Furthermore, VRE power plant design can be optimized from a system perspective rather than simply aiming at maximizing output at all times (e.g. wind turbine designs with a more steady generation output, orientation of PV plants)[25].

The maximum instantaneous generation share describes the maximum share of load covered by a certain type of generation technology. It gives an idea of what level renewable energy integration has reached and how concentrated RE generation occurs in the respective market. In 2013, Germany saw an instantaneous generation share for PV and wind combined of 71% on June 16 at 2 pm. ERCOT had a maximum instantaneous generation of wind power (negligible PV generation not considered) of 63% on March 3 at 2 am. In CAISO, the maximum instantaneous generation of PV and wind combined occurred on November 3 at 2 pm, reaching a generation share of 17%. Interestingly, CAISO´s instantaneous generation share was considerably lower despite a similar average generation share, suggesting a more diversified wind and PV generation than in ERCOT. Further research could shed light on this in more depth.

2.3 Policy Goals & Cost of PV and Wind Deployment

Greenhouse gas emission reduction goals

In California, the Global Warming Solutions Act (2006) requires statewide greenhouse gas (“GHG”) emission levels to be reduced to their 1990 levels by 2020. The policy instrument chosen to reach this goal is a Cap-and-Trade Program with compliance periods and year-specific amounts of allowances. In Texas, to date, there have not been any GHG emission goals installed, while in Germany, the government has the objective to reduce GHG emissions to 40% below their 1990 level by 2020, and at least 80% below their 1990 level by 2050. However, as of now, there is no national policy instrument to support this specifically. Rather, Germany participates in the European emission trading system which implements an EU-wide emission reduction target of 20% below 1990-levels until 2020, and 40% by 2030. Under the European Union Emissions Trading System (“EU-ETS”), some countries will reduce their emissions by more than the European average, some other countries by less, with specific mitigation efforts determined by European market forces.[20]

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[19] Dispatchable power plants depict power plants with energy storage, i.e. they can be dispatched independently of e.g. natural resource availability (e.g. electricity storage, conventional power plants) [5].

[20] See discussion on the so-called ”Energiewende-Paradoxon” in Germany in section 2.1.

Renewable energy deployment goals

On a U.S. level, no renewable energy ("RE") goals have been set to date. However, several policy instruments have been introduced to foster RE deployment. First there is a Production Tax Credit ("PTC") granted to wind and solar generators, being subject to repeated renewal periods. Also, an Investment Tax Credit has been imposed for RE projects, as well as a cash grant option for RE projects. On a state level, California adopted a Renewable Portfolio Standard ("RPS"), requiring a RE share of 33% with respect to electricity demand by 2020. Additional to the federal instruments, California chose multiple policy instruments to reach its RE goals. First, the RPS is tracked using a Renewable Energy Certificate ("REC") Program, with help of which each MWh of RE electricity is traded and thereby tracked. Additional policy instruments include the Renewable Auction Mechanism ("RAM"), Feed-in-Tariff ("FIT"), California Solar Initiative ("CSI"), Self-Generation Incentive Program ("SGIP") and the reduction of bureaucratic hurdles for RE projects. In California, in particular, RE generated outside the state can count towards the state-specific RPS goal, however to a share that is reduced every year. Texas also adopted an RPS, however expressed in capacity instead of share of demand. Thereby, 10´000 MW of RE capacity is required to be installed by 2025. In terms of policy instruments, Texas also installed a REC Program, with the capacity requirement being conversed in REC requirements.

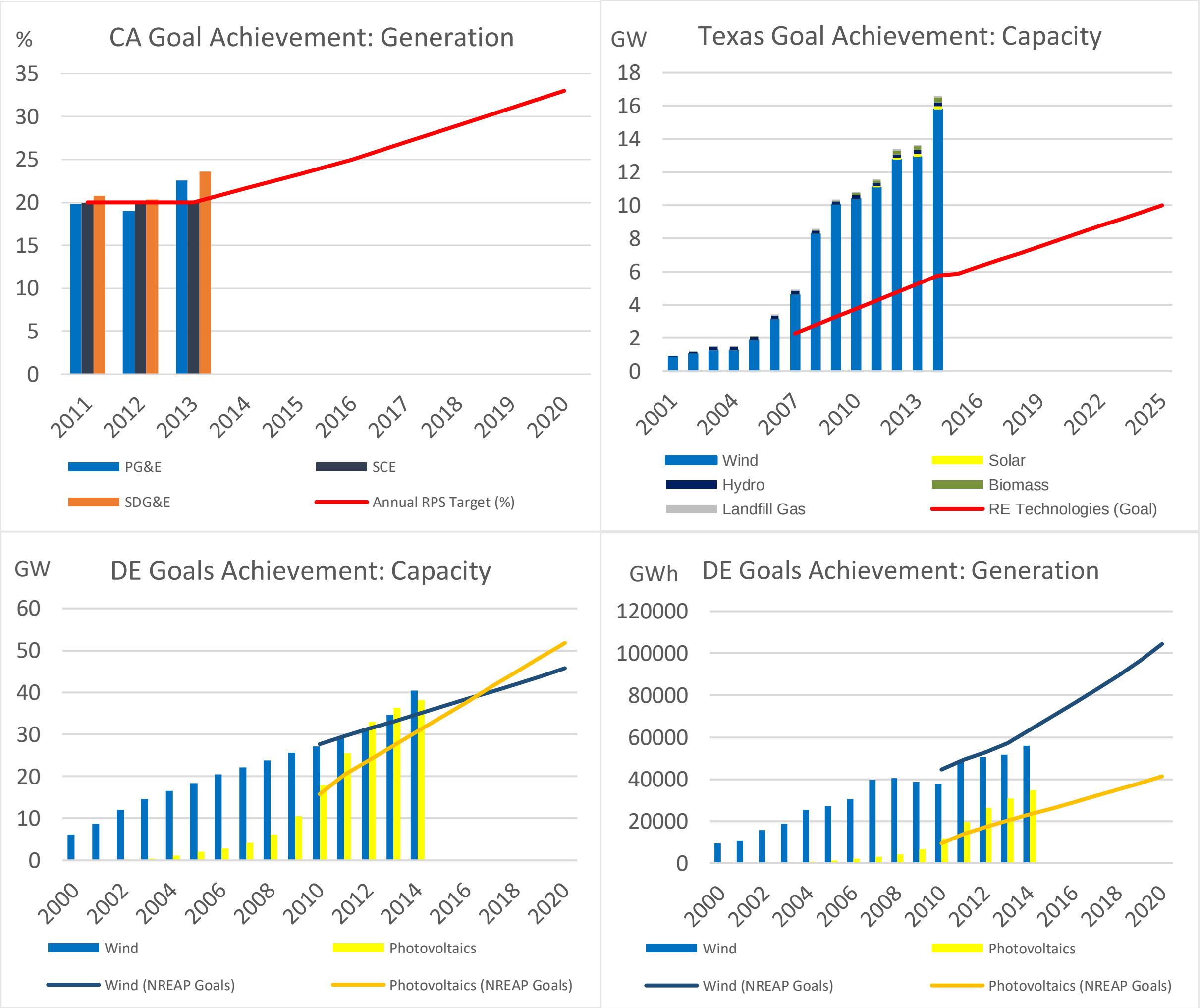

Figure 6, Source: EWI, data provided by BMWi [8], ERCOT [26] and Stanford

In Germany, the Energy Concept (2010) laid out RE goals requiring a RE share of 35% with respect to electricity demand by 2020, increasing linearly to a RE share of 80% by 2050. The policy instruments chosen to reach this RE goals are defined by the Renewable Energy Act (“EEG”), comprising a Feed-in-Tariff Scheme and a Market Premium Scheme. In spite of Germany being part of the European internal electricity market, up to now only RE plants at German location are eligible to receive support under the EEG. Also, the German government only counts German RE generation in order to determine its RE share.

Thus, objectives vary considerably between Germany, Texas, and California. By 2013, all three markets seem to be on track in reaching their respective goals (Figure 6). In Texas, the moderate goal of achieving 10 GW of installed RE capacity by 2025 was strongly overachieved, with an installed RE capacity of 16.6GW by 2014. In California, the first RPS compliance period from 2011-2013 required a RE share of 20% with respect to electricity demand, which was met by the three major utilities. Germany is also on track to reach its 2020 RE goals as stated in the National Renewable Energy Action Plan (“NREAP”). While wind capacity deployment was close to the path as stated by the goals, the PV capacity goals have been overachieved in the years 2011-2013.

Cost of wind and PV support schemes

In Germany, the cost of the FIT and Market Premium Scheme, the so-called difference cost, is added to consumer´s and part of the industry´s electricity bill as EEG levy.[21] The difference cost is calculated by summing up the total FIT and Market Premium payments minus the earnings from selling the renewable electricity on the electricity exchange.

In 2013, the total difference payments[22] of all renewable energy technologies amounted to 23 Bn USD_{2014}. The difference payments for wind were at 4.5 Bn USD_{2014}, translating into 8.6 cents USD_{2014}/kWh of wind generation, and the difference cost for PV were at 11.6 Bn USD_{2014}, which amounts to 37.6 cents USD_{2014}/kWh of PV generation. The average FIT tariff for a wind power plant commissioned in 2014 ranged from 11.2-12.4 cents USD_{2014}/kWh, while for PV it was in a range from 12.2-17.6 cents USD_{2014}/kWh. In California, the current starting prices of the Feed-in Tariff for generators with a capacity up to 3 MW, incorporating the Renewable Market Adjustment Tariff pricing mechanisms, ranged from 6.5- 8.9 cents USD_{2014}/kWh for solar and were at 8.9 cents USD_{2014}/kWh for wind. These starting prices are adjusted upwards or downwards depending on the number of subscriptions [27][28][29][30].[23]

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[21] Part of Germany´s industry, mainly the energy-intensive industry facing international competition, benefit from exemptions from surcharges and taxes. Commercial and industry electricity prices thus vary according to the degree of exemptions, which, in turn, depend on their electricity consumption and their exposure to international competition.

[22] EEG difference payments = total EEG payments to generators - revenue from selling the electricity on the wholesale market

[23] For ERCOT there is no information available as there is no FIT system implemented and the implicit price of the Renewable Energy Portfolio Standard program could not be analyzed within the scope of this work. The latter holds true also for the RPS program in California.

2.4 Demand Structure

There are significant differences in the demand structure between the two U.S. states and Germany. While in CAISO and ERCOT the demand is higher in the summer than in the winter, the demand in Germany follows the opposite pattern (Figure 7).[24] The annual peak demand in Germany is expected to occur during winter evenings between 6:00 and 8:30 pm, whereas in CAISO and ERCOT it is expected to occur in summer afternoons between 3:00 and 7:00 pm. Hence, the capacity credit (also called capacity value) of PV during annual peak demand is expected to be significant for CAISO and ERCOT, translating in a substantial contribution to security of supply.[25] The capacity credit of PV in CAISO is measured using the Effective Load Carrying Capability ("ELCC") methodology and reported to range from 60-75% at current deployment levels [32]. In contrast, the capacity credit of PV during annual peak demand in Germany is zero, since there is no solar irradiation in winter evenings.

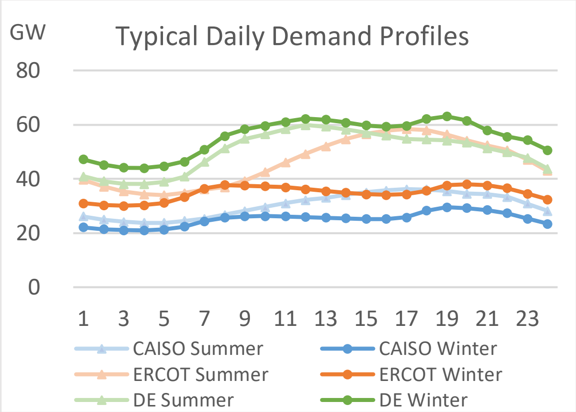

Figure 7, Source: EWI, data provided by ENTSO-E [31] and Stanford

The capacity credit or capacity value of wind during times of annual peak demand is about 1-10% in Germany. In ERCOT, the capacity credit of wind during annual system peak is reported to range from 3.9-20.3% [33]. In California, the capacity credit of wind during peak demand is measured using the ELCC methodology, resulting in a range from 24-39% [32].[26] Besides the calculation method, the main drivers of the difference in capacity credits are the general resource quality and the daily structure of wind power generation. In Germany, there is no clear daily structure for wind energy output; however there tends to be more wind in the afternoon than during any other time of day. The daily structure of wind energy in Texas and California also seems to show more wind in the afternoon at peak demand, thus increasing the capacity credit of wind.

In summary, both the contributions of solar PV and wind to security of supply are higher in Texas and California than in Germany. The amount of system flexibility options that are needed to cover annual peak demand in case of wind and solar energy are not available is therefore expected to be smaller in the two U.S. states relative to Germany. Less system flexibility options might reduce overall system costs.

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[24] 2013 data

[25] Loosely speaking, a capacity credit reflects a generator's ability to match (peak) demand. More precisely: A capacity credit is the share of installed capacity that is available for generation at a certain level of confidence. However, the usage of the term capacity credit often refers only to the capacity credit of the relevant hours regarding the annual peak demand in the market. An in-depth quantitative analysis of the capacity credit of PV in CAISO and ERCOT needs further analysis.

[26] For an in-depth analysis of the differences in the capacity credit calculation methodologies, further research is necessary.

2.5 Grid Stability

There are significant differences in the size of grid as well as in grid stability between California, Texas and Germany. A measure of grid reliability is the System Average Interruption Duration Index ("SAIDI"), which gives the average interruption time in the low and medium voltage grid for final consumers. The German grid infrastructure offers a relatively high reliability standard with an average interruption time of 15.3 minutes in 2013. The average interruption times is much higher in ERCOT and CAISO. Figure 8 shows the interruption time for Germany as well as the range for average interruption for the different utilities in CAISO and ERCOT. In spite of the strong deployment of wind and PV in Germany, electricity system stability has not decreased over the last years. In CAISO, the interruption was relatively high in 2011, but has been decreasing since then. In ERCOT the interruption time has been increasing since 2009. Worries ab out grid stability due to the fast integration of many volatile renewable energies into the system my hamper renewables integration.

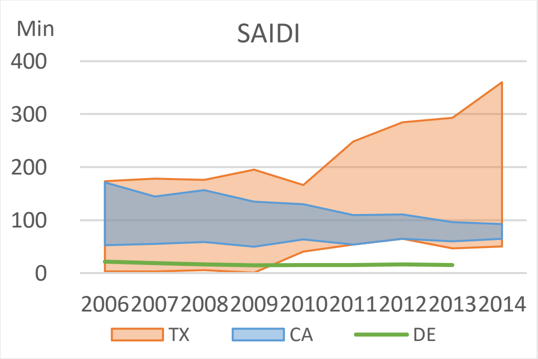

Figure 8, Source: EWI, data provided by BNetzA [34] and Stanford

CAISO's grid encompasses three quarters of California and spans 26´000 circuit miles of transmission network. ERCOT's electricity network consists of around 43´000 circuit miles of transmission network. In Germany a total of approximately 1.1 million circuit miles of electricity network exists, whereof 22´000 circuit miles are the transmission networks operated by the TSOs. Thus the transmission network of ERCOT is 1.6 times as large as CAISOs transmission grid and 1.9 times as large as the German transmission network.

In CAISO, curtailment is infrequent and not tracked [35]. With the expected strong growth in VRE capacity in the years to come, however, curtailment due to over-generation may increase. In view of this, CAISO is exploring market-based solutions to addressing over-generation. With a reduction of the bid floor to -150 USD, generators are incentivized not to generate when prices are negative. In ERCOT, curtailments peaked in 2009, jumping from about 8% of potential generation[27] in 2008 to 17% in 2009 (Figure 9). However, transmission capacity expansion and the market redesign including introduction of locational marginal pricing (LMP) and faster schedules brought curtailments down to 4% in 2012 and just above 1% in 2013. In Germany, curtailments were below 0.5% from 2009-2012, with a share of 0.3% of potential generation in 2012

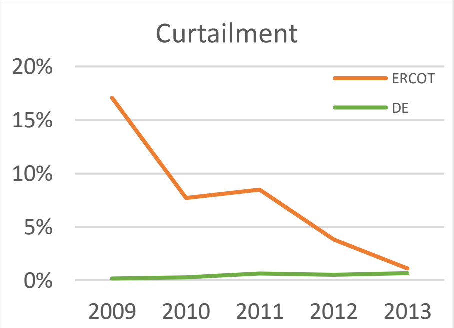

Figure 9, Source: EWI, data provided by BNetzA [34] and Stanford

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[27] Potential generation = actual generation + curtailed electricity

(data for 2013 not yet available). The largest part of curtailments (93%) were from wind power plants while only around 4% of curtailed energy was from PV plants. With respect to negative prices, in the current remuneration scheme, RE generators still have an incentive to generate when prices are negative.[28]

For the integration of renewable energies grid access is an important factor. The duration until a power plant can be connected, as well as connection costs, may impact the integration of renewables. In Germany generators only pay for grid connection to the closest grid connection knot. Grid extensions at the distribution and transmission voltage level are "socialized" and paid by the consumers as grid charges. Furthermore, the TSOs and Distribution system operators ("DSOs") are obliged to connect every power plant to the grid.[29] In contrast, in the US, the Federal Energy Regulatory Commission ("FERC") issued Large and Small Generator Interconnection Procedures stating that generators bear the costs from the generator to the next interconnection point to the transmission network while transmission and distribution network upgrades are generally paid by the transmission provider and ultimately its customers [37][38].

2.6 Electricity Prices, Fuel Cost & CO2 Cost

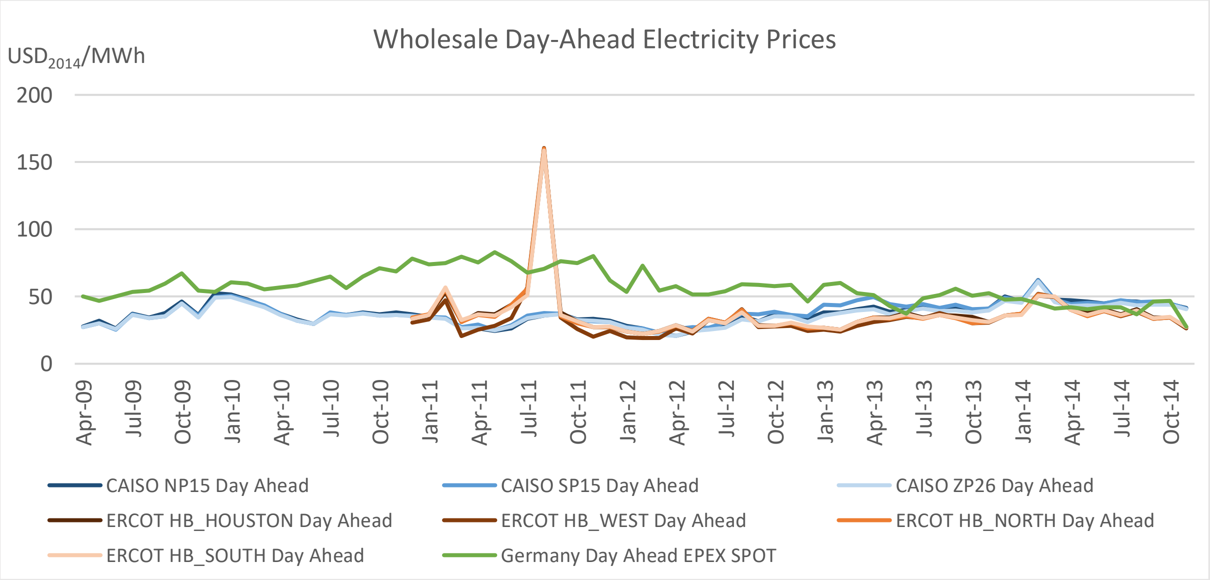

Figure 10, Source: EWI, data provided by EEX [39] and Stanford

A direct comparison of wholesale electricity prices shows that average wholesale day ahead prices in CAISO and ERCOT were lower than in Germany, however prices converged from 2011-2013 (Figure 10).

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[28] Note, from 2016 onwards this will no longer be the case. RE generators will not receive any support in hours, when market prices have been negative for more than 6 hours in a row and/or for wind generators if the rated power is >3MW [36].

[29] There are some offshore wind power plants that cannot be connected for the moment. However, these wind power plant operators are compensated for the loss: They get the FIT for the energy that these power plants would have produced, if they were connected. Nonetheless, this delay in connection already hamper further investments in wind offshore. One reason is that the maintenance cost are higher non-connected plans than for connected once.

When comparing wholesale day ahead electricity prices, several factors have to be considered. First, fuel prices for conventional power plants vary considerably (Figure 11). Due to the shale gas revolution in the U.S., natural gas prices have plunged, being at a level of around one third of German natural gas prices. In Texas, a hard coal producing state, hard coal prices are considerably lower than in California and Germany where the largest part of hard coal is imported. Among the three markets, lignite is used only in Germany, where it represents a source of cheap electricity generation (with some externalities being neglected). Due to its rather low energy density it is mostly used in close proximity to the mines. Another important factor influencing the wholesale electricity price is the CO$_2$-allowance price level, and, via dynamic investment effects, the extent to which the power sector is granted free CO$_2$-certificate allocations (which was partly the case in Germany until 2013). The Californian Cap-and-Trade program was launched in 2012, showing prices of 11.7-25 USD$_{2014}$/tCO$_2$e and a yearly average price of 13.8 USD$_{2014}$/tCO$_2$e in 2013. In 2014 the price decreased to 12 USD$_{2014}$/tCO$_2$e. In Texas, there is no Cap-and-Trade program installed to date.

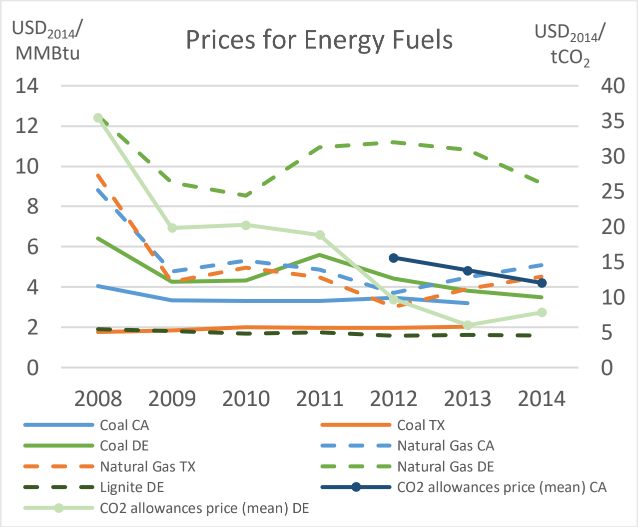

Figure 11, Source: EWI, data provided by BMWi [8], EEX [40], EIA [41][42][43], ICE [44] and McCloskey [45]

Other factors include, amongst others, fossil fuel subsidy levels, work force costs and the merit order of the power plant mix.

Electricity: Retail prices

In California, Texas and Germany retail price levels for consumers, the commercial sector and the industry vary. In the (energy-intensive) industry sector, California shows the highest prices and Texas the lowest while Germany and Texas were at a very similar level (Figure 12) [46]–[48].

In Texas and Germany the prices for energy-intensive industrial consumers were decreasing in the last years, whereas in California these prices were slightly increasing. Some part of the price reduction in Germany is based on the merit order[30] effect that reduces the wholesale market price: Since heavy industry is largely exempt from refinancing the RE payments via the EEG levy it receives a net-benefit from the RE support scheme (see section 2.3). However, most of the decrease is likely due to the economic crisis in Europe – which has aggravated an overcapacity of electricity generation - and the sharp fall in the price of imported hard coal. The price reduction in Texas can be partly explained by the gas price reduction in the context of shale-gas production in Texas. The price increase in California

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[30] The merit order describes the ordering of power plants based on their short-term marginal generation costs. Since many VRE, e.g., wind and solar energy, have marginal generation costs close to zero, they replace the electricity generation by conventional power plants that have relatively higher variable generation costs. In hours with high generation from renewables, power plants with low generation costs determine the price [5].

can be partly explained by the adoption of the Cap-and-Trade System for GHG Emissions, i.e. a measure to internalize the external costs of electricity generation.

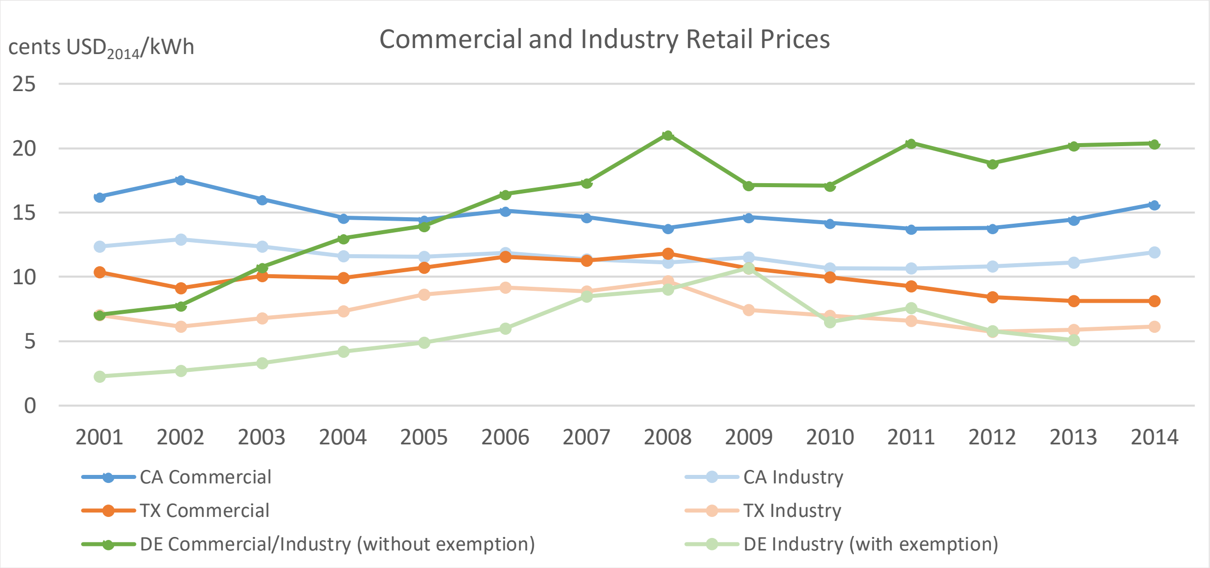

Figure 12, Source: EWI, data provided by BDEW [47], BMWi [46] and EIA [48]

Prices for the commercial and industry sector without exemptions were increasing in Germany over the last years (Figure 12). In California, prices for the commercial sector remained nearly constant and were decreasing in Texas.

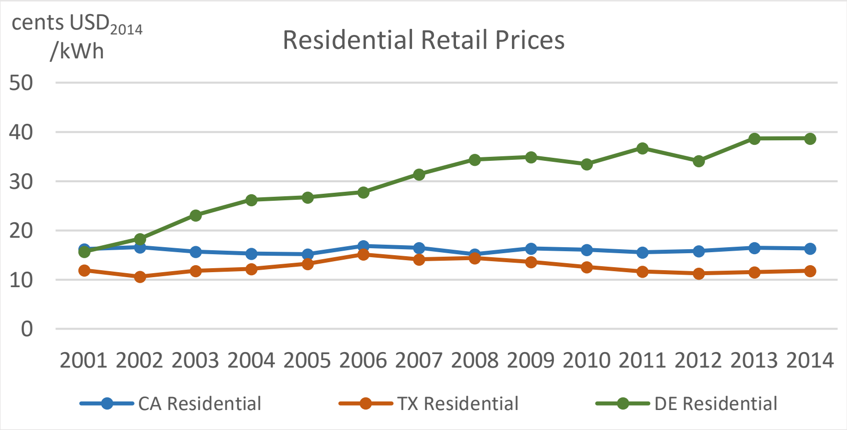

Figure 13, Source: EWI, data provided by BDEW [47] and EIA [48]

The residential retail prices were increasing in California and Germany during the last years (Figure 13). However, the price increase was steeper in Germany than in California. In Texas residential retail prices for consumers were decreasing. On average, about 30% of the price increase in Germany is driven by the EEG surcharge which has increased from about 1.9 cents USD_{2014}/kWh in 2009 to 8.3 cents USD_{2014}/kWh in 2014. RE deployment has also led to increases in grid cost, and thus in grid-fees in Germany, which also contributes to the increase in commercial and residential electricity prices. Note that the net price effect of RE promotion might be lower since the merit order effect of RE in Germany reduces average wholesale prices which will be passed to end consumers due to competition, eventually. However, to quantify this, further in-depth research is needed including an investigation on the system effects of RE deployment.

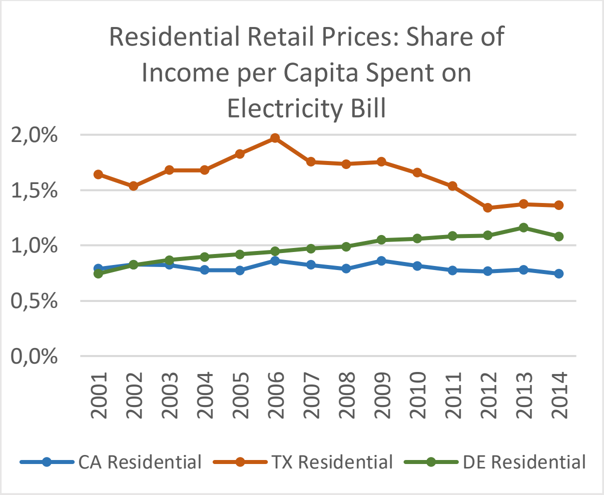

Figure 14, Source: EWI, data provided by BDEW [47] and EIA [48]

Though retail prices are significantly higher in Germany, it is interesting to note that nevertheless the share of income spend on electricity is highest in Texas (about 1.5%), followed by Germany (about 1%) and California (slightly below 1%), see Figure 14. The main reason for this is the significantly lower per capita consumption of electricity in Germany.

To summarize, in California and Germany, the effect of increasing retail prices has been cushioned by generally lower electricity consumption levels combined with comparably higher incomes.

3 IMPLICATIONS FOR RE DEPLOYMENT IN THE FUTURE

3.1 High Natural Resource Quality vs Low Fuel Prices: Opportunity & Challenge

According to estimates, RE at German locations could become only competitive in European electricity markets at CO_2 prices above the levels currently envisaged by European policymakers. This can be explained partly by the inferior quality of the natural resources, partly because Germany has built-up significant wind and solar capacities already which – due to broadly identical meteorological conditions – undermine the business for additional RE installations because of their decreasing market value.[31] Thus unless the price for CO_2 increases to levels far above the current level, additional deployment of RE in Germany will continue to require support. However, with respect to the retail market, increasing residential electricity tariffs and falling rooftop PV system costs have recently facilitated after-tax grid parity[32] at the residential level in Germany, encouraging households to self-consume the electricity generated form their PV systems. The flat residential electricity rate was equal to 38.2 cents USD_{2014}/kWh in 2013, well above the generation costs of rooftop PV systems lying in the upper LCOE range (10.4-19 cents USD_{2014}/kWh) in 2013 [50].

The situation is very different in the U.S. On the one hand, RE face stiffer competition from conventional generation in the U.S. than in Germany. Fossil fuel prices are much lower in California and Texas than in Germany, in particular for natural gas and hard coal. Although the Californian price for CO_2 emissions currently slightly exceeds the European one, this difference does not fully make up the fuel cost differential. In Texas, moreover, there is no price on CO_2 emissions.

On the other hand, the quality of the natural resource make RE production much more attractive in the U.S. compared to Germany.

California and Texas feature almost double the solar irradiance available in Germany. Since PV module prices are global, and thus should be roughly identical for the three regions, levelized cost of electricity (LCOE) should be much lower in the two U.S. regions studied than in Germany. However, to date, LCOE still span broadly similar ranges in the three markets due to higher non-hardware costs for PV system deployment like installation cost and bureaucratic burdens.

Thus, assuming that installation markets are maturing, and that bureaucratic burdens might be relaxed, relatively high Californian electricity prices could provide a case for increased residential PV deployment - even more so, as the high peak demand coincidence of PV further increases its market value at the low penetration rates currently achieved.[33] Utility-scale PV deployment in California is

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[31] The market value is given by the weighted average spot market price that a VRE generator would be able to receive by selling the VRE electricity on the spot market [5].

[32] As stated in the Case Study “Germany´s Wind and Solar Deployment 1991-2015: Facts and Lessons Learnt.” [5], “Grid parity is known as the point in time at which LCOE of the rooftop PV systems reach the level of the residential electricity tariff [49]. Grid parity does not necessarily indicate that investment into auto-consumption is efficient at the level of the entire economy, since retail prices often are distorted by state-induced cost components such as taxes or levies. This, in particular, is the case in Germany where state-induced cost components make up roughly half of total retail prices.”

[33] CAISO announced in June 2015 the creation of new market regulations and market structures to facilitate integration of rooftop PV, storage and demand response [51].

already experiencing an uplift.[34] In Texas, however, in spite of the quality of the solar resource, lower fuel and retail prices might remain a challenge for residential PV for the years to come, unless a PV support scheme or a Cap-and-Trade system for CO_2 allowances were put into place.

Also with respect to wind resource quality, both California and especially Texas outperform German conditions by far. The range of quoted LCOE is narrower in both U.S. markets, suggesting a broader potential of top wind locations compared to Germany. Furthermore, LCOE of wind are close to being competitive to wholesale prices both in California and in Texas. Thus it is no surprise that Texas has already strongly increased its wind capacity in recent years even though there were only moderate or no promotion schemes in place. Considering the state´s high wind resource quality, the use of wind energy could continue to grow in the future even without a price on CO_2.

3.2 Making Grid Access Easy Incentivizes the Built-out of Renewables

Grid access is an important factor regarding the integration of renewables into the electricity system. Compared to Texas and Germany, grid connection might be a bigger challenge in California. In Germany, generators only pay for grid connection to the closest grid connection point. Grid extensions at the distribution and transmission voltage level are “socialized”, i.e., not entirely borne by those who cause the additional grid costs (e.g., power plant investors), but paid by the consumers by increased grid charges. In Texas, the transmission system is also paid by the end consumers only.[35] Furthermore, both in Germany and in Texas grid connection is implemented relatively fast.[36] In contrast, it is more arduous to interconnect renewables into the system in California.[37] Making grid access easy and cheap is an important driver for the deployment of renewables.

3.3 Policy Instruments Interact and Should Be Aligned

The European greenhouse gas emission Cap-and-Trade system has experienced very low certificate prices in recent years, due to the economic crisis in the wake of the financial crisis as well as the high admission of JI/CDM certificates especially from Russia, Ukraine, China and India [53]. In addition, the fast deployment of RE in Germany, driven by a RE support scheme in parallel to CO_2 pricing, further depressed the European CO_2 price. While Germany’s fast deployment of RE has contributed to a reduction of costs of these technologies (though at a relatively high price for the German electricity consumer), it did not have any direct impact[38] on the European wide CO_2 emission reduction level (due to the missing coordination with the European-wide EU-ETS cap for CO_2 allowances).

Any policy that aims at reducing climate gas emissions effectively needs to set a (sufficiently) high price on GHG, in particular CO_2. This may be implemented via a Cap-and-Trade scheme or an emissions tax. In any event, any ambitious GHG target will turn into CO_2 prices which most likely will make RE

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[34] Only in June 2015, the largest ever operational PV plant, “Solar Star”, with 579 MW peak capacity went online in the CAISO area [52].

[35] As an expert in the Stanford Workshop states: “We view the transmission system as a highway system; it’s paid for by load”.

[36] E.g. an expert in the Stanford workshop estimated that the ERCOT interconnection process would take roughly one year.

[37] As an expert from the Stanford stakeholder workshop states: it is a “long, arduous, expensive prospect to interconnect utility scale projects in California.”

[38] Indirect contributions to international climate policy are expected to exist. However, they are difficult to quantify and need further research.

competitive at some point in time, depending on the RE LCOE at the available locations and in the given system configuration, and the cost of alternative mitigation measures. From a European climate policy perspective, additional instruments for RE support may be redundant if not coordinated with the Cap-and-Trade System. However, from a global climate policy perspective, potential additional effects arising from RE technology cost reduction, technology transfer and signaling need to be considered, too.

With a technology-neutral approach to GHG mitigation, the portfolio of RE deployment would develop less quickly, and in a less diversified manner than it has in Germany. On the contrary, it would be focused on the cheapest combinations of RE technology and location. In the context of the European emission trading system Germany would most likely have seen considerably less RE investments, because other mitigation options (e.g. coal-gas-switch, or demand reduction) and other RE locations (e.g. wind in Ireland or solar in Spain) would have been more competitive. Thus, at current CO_2 price levels, explicit and implicit financial support for RE generation continues to be a necessary condition for RE deployment in Germany. However, one technology which stands a chance to become competitive at German locations at present in a European technology-neutral GHG regime seems to be wind on-shore.

In contrast, the race may be more open between PV and wind in California and Texas. Eventually, competitive markets equipped with a reliable price signal for CO_2 will be best suited to determine the most efficient RE deployment choice. The installation of parallel targets such as e.g. a binding RE target – which is then implemented via a FIT or an RPS – is typically based on additional policy goals apart from GHG mitigation. It will typically counteract economic efficiency and possible interactions need careful assessment.

3.4 Wind and PV Deployment Dynamics Need to Be Anticipated

The German and Texas experiences show that strong PV and wind deployment dynamics trigger important system effects, such as e.g. the need for network expansion due to different generation clusters, or the need for more flexible residual capacity. Such knock-on effects of RE deployment should therefore be anticipated, closely monitored, and well-managed. The German experience shows that keeping a high standard of system stability and strong wind and PV deployment can go hand in hand when closely monitoring and adjusting the system.

3.5 Market Design Matters for RE Integration

Natural resource forecast accuracy increases strongly the shorter the forecast period gets. Thus, shorter periods between trading and delivery of electricity allow more market participants to enter the market, both on the wholesale and balancing reserve power markets. In particular, shorter scheduling and dispatch intervals play an important role. This is important for any system in which RE are integrated in the electricity market, making them more competitive.

The CAISO and ERCOT real-time markets show that schedule adjustments up to five minutes before delivery are feasible. An important enabler for shorter gate closure times is the inclusion of grid capacity constraints in the market price, as demonstrated by the locational marginal prices in CAISO and ERCOT. To give an example for successful market rules adjustments, ERCOT reduced the minimum curtailment period from fifteen to five minutes which led to a substantial decrease in wind curtailments. In this respect, German market design still exhibits substantial improvement potential, e.g. regarding shorter gate closures, and an improvement of cross- border intra-day trading within the European internal market as well as, on a more general level, improvements in the design of the RE support scheme, the grid fee calculations, and the balancing market requirements.

Regarding the RE support scheme design, the distribution of risk is an important factor. The German experience shows that relieving the investor from the price risk (by guaranteed FIT) and exposing him only to the volume risk strongly facilitates capital sourcing. However, the price risk of the RE did not disappear, but it was shifted from the RE investors to the electricity consumers. Protecting selected investor groups from risk typically causes inefficient investment decisions, and leads to pressures from the hitherto unprotected market participants to receive corresponding protection themselves.

4 CONCLUSION & FURTHER RESEARCH

The comparison shows that wind and solar energy has been rolled out very fast in Germany relative to California and Texas (in terms of capacity), especially taking into account the lower natural resource quality of wind and solar in Germany. We find that the extent of wind and solar deployment in Germany was facilitated by two major factors: First, a generous, risk-relieving support scheme refinanced by the electricity consumer via the EEG law; and second, a favorable grid regime reducing time and cost of connecting RE generators to the grid.

For the U.S. markets studied, this analysis points at some significant barriers for a faster RE roll-out: the absence of an equally generous RE support scheme; the higher private risk for the RE investor; institutional barriers relative to time and cost of grid connection; as well as relatively lower energy cost in general. Thus, there seem to be three levels of improving the situation from the perspective of RE investors in the U.S. As a first step, institutional barriers and transaction cost could be minimized. As a next step, technology neutral CO_2 prices could be introduced (Texas) or increased (California) in order to appropriately internalize part of the external cost of fossil fuel use. As a third step, if there were additional reasons for a promotion of RE apart from climate policy, e.g. specific RE goals, policymakers could consider specific RE promotion schemes including a rolling-over of risk from the RE investor to the general public.

This study was intended to provide a first overview and comparison between the experiences of Germany, Texas, and California with the deployment of renewable energy sources in the electricity sector, in particular for wind and solar. Further research should be undertaken to look at some of the issues identified in this study in more detail. For example, the distribution of risk seems to be widely different between the markets, with conventional generators, RE generators, grid companies, and electricity consumers being heterogeneously affected. This study has not been able to analyze these effects in detail, or even to quantify them. Herein lies an important field of future research.

Also, it is necessary to understand the 'LCOE paradoxon' in more detail, i.e. the fact that LCOE cost differentials between Germany and the U.S. do not seem to fully reflect the U.S. advantage in the quality of the natural resources. Thus, on the one hand, the quality of the resource (in terms of cost and volume, i.e. locations) could be compared in more detail. On the other hand, the difference in the installation cost of wind and solar capacities need to be given more attention. In this context, it might be interesting also to look at potential differences in financing conditions, e.g. the different opportunity cost of investments.

An additional field of comparative research should look at the differences in market design and market structure, and their relative impact on the propensity of investors to build RE capacities. Here, an important difference is certainly given by different expectations relative to the development of electricity demand on the one hand, and of fossil fuel prices on the other hand. In this context, the structure of the demand side – including the structure of exports/imports should be investigated in more detail. But specific rules on e.g. the curtailment of wind and solar, or, respectively, the impact of 'negative prices', need to be taken into account, too. Furthermore, any conclusive assessment of the value of RE generation needs to be based on an in-depth investigation on existing fossil fuel subsidies and neglected externalities arising from fossil fuel and nuclear generation which are borne by the state and thus eventually the society.

Also, more attention needs to be devoted to the political framework and the political economy encompassing and defining energy policy in the three markets. Germany is a country with rather limited supplies of fossil fuels, and a high share of imports. Thus, beneficiaries of a RE support scheme greatly outnumber those who suffer from the implied devaluation of fossil resources. This might lead to different political dynamics than in the U.S. where most of the fossil fuel consumed comes from within the country.

Finally, it would be most interesting to compare the electricity systems of Germany, California, and Texas on the basis of quantified models. Thus, it would be possible to derive more detailed insights into the absorptive capacity of the three systems for different levels of wind and solar capacities, shedding more light especially on the potential development of capacity credits and instantaneous generation. Moreover, such an approach would also allow to study in more detail the diversification potential in the three markets which might arise from e.g. mixing wind and solar, mixing locations with different meteorological patterns, or from an increased use of exports and imports. Also, it would be interesting to derive and to compare optimal pathways based on similar, technologically neutral GHG mitigation policies, and the relative role of wind and solar deployment between them. Such an analysis would also provide insight on the different roles of the legacy investments in the three markets, and in the shape and development of the merit order at different levels of RE capacities. In this context, it would also be important to compare the implications for RE technology design, e.g. for the specification of wind turbines or the orientation of new solar installations as a function of the RE penetration level already achieved in the markets.

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