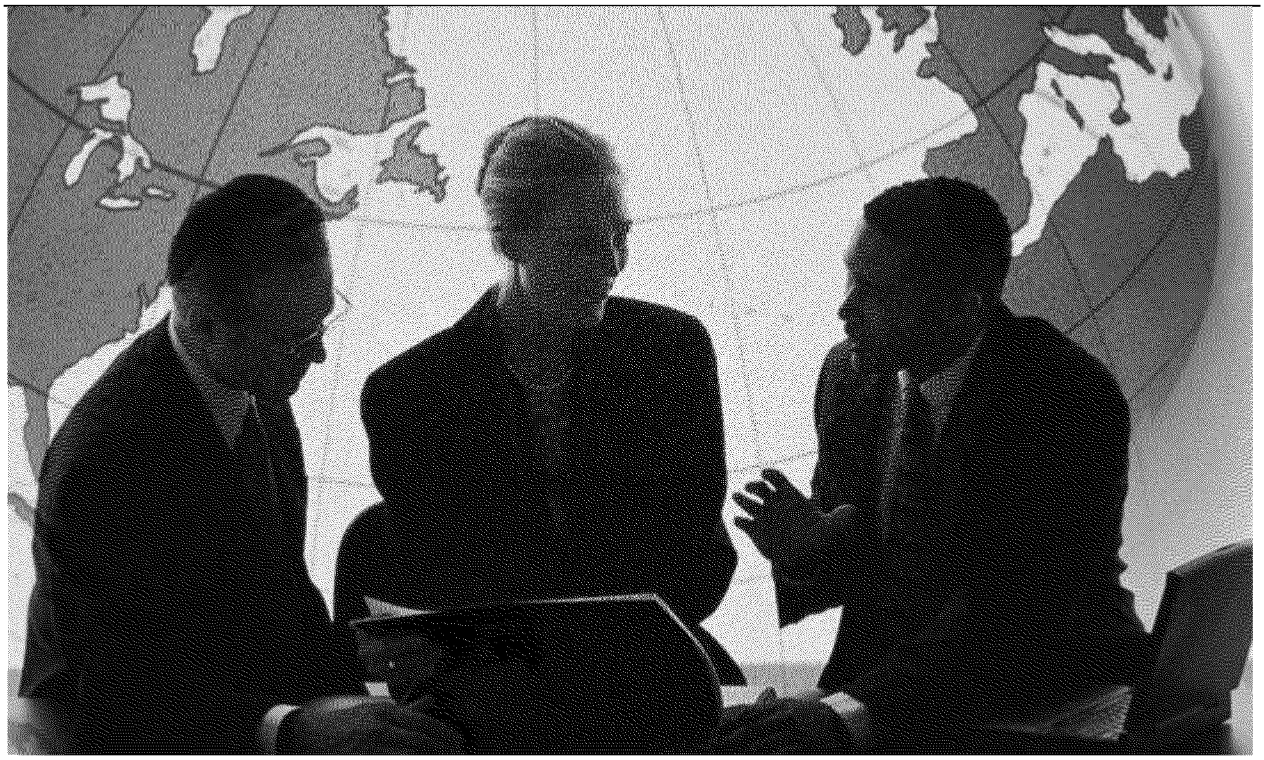
ATTACHMENT 3



Emissions Comparison for a 20 MW Flywheel-based Frequency Regulation Power Plant

Beacon Power Corporation
KEMA Project: BPCC.0003.001
May 18, 2007
Final Report with Updated Data

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EXECUTIVE SUMMARY

KEMA Inc. was commissioned by Beacon Power to evaluate various performance aspects of the Beacon Power 20 MW flywheel-based frequency regulation power plant, including its emissions characteristics. To support the emissions evaluation, a detailed model was created to compare the emissions of CO_2, SO_2 and NO_x for a Beacon Power flywheel plant versus three types of commercially available power generation technologies used in the market to perform frequency regulation ancillary services.

The comparison of generation technologies included a typical coal-fired power plant, natural gas combustion turbine, and pumped storage hydro system. Emissions from the coal and natural gas-fired generation technologies result directly from their operation because they burn fossil fuels. In contrast, emissions for the flywheel and pumped hydro energy storage systems occur indirectly because they use some electricity from the grid to compensate for energy losses during operation. The emissions characteristics for these losses are based on the emission characteristics for the specific ISO area where the flywheel and pumped storage system are being used.

The mix of power generation technologies and average system heat rates for fossil-based power generation systems varies across regions in the United States. To obtain a regionally adjusted emissions comparison, system data specific to three Independent System Operator (ISO) regions were examined: PJM (Mid-Atlantic), California ISO (CAISO), and ISO New England (ISO NE). Data for each of these ISOs was extracted from the Department of Energy (DOE) Energy Information Administration (EIA) and Environmental Protection Agency (EPA) eGRID databases. Model calculations assumed typical heat rate and efficiency data for each type of generation.

For coal and natural gas-fired generation, KEMA's research found that frequency regulation results in increased fuel consumption on the order of 0.5 to 1.5%.[1] This finding is supported from estimates made by a U.S. DOE National Lab, information obtained from the ISOs, and from a European study that evaluated electricity producers to determine whether power plants providing frequency regulation had an increase in fuel consumption and maintenance requirements. This effect was reflected in the model.

Based on the above data, model analysis showed that flywheel-based frequency regulation can be expected to produce significantly less CO_2 for all three regions and all of the generation technologies, as well as less NO_x and SO_2 emissions for all technologies in the CAISO region. The flywheel system resulted in slightly higher indirect emissions of NO_x and SO_2 in PJM and ISO NE for gas-fired

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[1] A 0.7% increase in fuel consumption due to frequency regulation was assumed in the model for this study.

generation. This is because PJM and ISO NE's generation mix includes coal-fired plants, and make-up electricity used by the flywheel and hydro systems reflects higher NO_x and SO_2 emissions from electricity generated in those areas. This effect was greatest in PJM because it has proportionally more coal-fired plants than ISO NE.

When the flywheel system was compared against "peaker" plants for the same fossil generation technologies, the emissions advantages of the flywheel system were even greater. Model results for each of the ISO territories are summarized in Table 1, Table 2, and Table 3 on the following pages.

Table 1: Emissions Comparison for PJM

Flywheel Emission Savings Over 20-year Life: PJM

	Coal		Natural Gas		Pumped Hydro
	Baseload	Peaker	Baseload	Peaker	
CO2					
Flywheel	149,246	149,246	149,246	149,246	149,246
Alternate Gen.	308,845	616,509	194,918	224,439	202,497
Savings (Flywheel)	159,599	467,263	45,672	75,193	53,252
Percent Savings	52%	76%	23%	34%	26%
SO2					
Flywheel	962	962	962	962	962
Alternate Gen.	2,088	5,307	0	0	1,305
Savings (Flywheel)	1,127	4,345	-962	-962	343
Percent Savings	54%	82%	n/a	n/a	26%
NOx					
Flywheel	259	259	259	259	259
Alternate Gen.	543	1,381	105	154	351
Savings (Flywheel)	284	1,122	-154	-105	92
Percent Savings	52%	81%	-148%	-68%	26%

Table 2: Emissions Comparisons for CAISO

Flywheel Emission Savings Over 20-year Life: CA-ISO					
	Coal		Natural Gas		Pumped Hydro
	Baseload	Peaker	Baseload	Peaker	
CO2					
Flywheel	91,079	91,079	91,079	91,079	91,079
Alternate Gen.	322,009	608,354	194,534	223,997	123,577
Savings (Flywheel)	230,930	517,274	103,455	132,917	32,498
Percent Savings	72%	85%	53%	59%	26%
SO2					
Flywheel	63	63	63	63	63
Alternate Gen.	1,103	2,803	0	0	85
Savings (Flywheel)	1,041	2,741	-63	-63	23
Percent Savings	94%	98%	n/a	n/a	27%
NOx					
Flywheel	64	64	64	64	64
Alternate Gen.	499	1,269	80	118	87
Savings (Flywheel)	435	1,205	16	54	23
Percent Savings	87%	95%	20%	46%	26%

Table 3: Emissions Comparisons for ISO-NE

Flywheel Emission Savings Over 20-year Life: ISO-NE					
	Coal		Natural Gas		Pumped Hydro
	Baseload	Peaker	Baseload	Peaker	
CO2					
Flywheel	106,697	106,697	106,697	106,697	106,697
Alternate Gen.	304,759	608,354	197,359	227,249	144,766
Savings (Flywheel)	198,062	501,657	90,662	120,552	38,070
Percent Savings	65%	82%	46%	53%	26%
SO2					
Flywheel	270	270	270	270	270
Alternate Gen.	1,300	3,303	0	0	367
Savings (Flywheel)	1,030	3,033	-270	-270	96
Percent Savings	79%	92%	n/a	n/a	26%
NOx					
Flywheel	115	115	115	115	115
Alternate Gen.	416	990	58	85	157
Savings (Flywheel)	301	875	-58	-31	41
Percent Savings	72%	88%	-101%	-36%	26%

The emissions estimates under the scenarios listed above show highly favorable comparisons for the flywheel across all generation technologies.

The remaining sections of the report provide the assumptions that were used in the modeling as well as further insights and analysis.

A full summary of the emission comparisons is provided in Section 4.3. The final data was based on the operation of a "typical" power plant for each of the categories. Analysis using known heat rates for a specific generating plant performing regulation would improve the accuracy of model comparisons relative to that specific plant.

1. Introduction

Beacon has requested that KEMA perform a two-phased technology evaluation of a 20 MW flywheel technology contrasting flywheel-based frequency regulation with conventional fossil, hydro and lead acid solutions with respect to:

Phase I: Environmental impact evaluation of the flywheel system with other commercially utilized frequency regulation technologies, bidding into the ancillary services market.

Phase II: Benefits of fast response to grid frequency regulation management, updated life-cycle environmental impacts and cost-performance analysis of the flywheel.

This report addresses Phase I, evaluating the environmental impact of the flywheel, compared to other existing commercially available technologies for frequency regulation as an ancillary service.

2. Scope of Work and Work plan

2.1 Technologies

KEMA evaluated the following technologies for frequency regulation at three locations. One in the CAISO service area, one in the PJM service area and one in the ISO New England service area:

a) Beacon Flywheel (Nominal power at 20MW plant)

b) Conventional coal-fired fossil generating plants (Base Load and Peaker plants)

c) Conventional gas-fired fossil generating plants (Base Load and Peaker plants)

d) Pumped Hydro Storage

2.2 Environmental Impact Evaluation

The Beacon flywheel is evaluated against other generation for the purpose of frequency regulation based on emissions and includes the following:

a) Impact of the operation of the storage system to the environment - Quantified in tons of CO_2, NO_x, and SO_2.

b) Assumptions are provided to Beacon and collectively accepted before the analysis commences.

c) As part of the assignment a proprietary environmental evaluation tool was developed by KEMA.

d) The deliverable for the Phase I task is this report on the possible emissions savings.

3. Assumptions and Approach

3.1 General Assumptions Emissions Calculations

For coal and natural gas, a simplified approach was used to characterize whether plant efficiencies at altering loads have a large impact on actual emissions output. For coal and natural gas, emissions can vary depending on other factors. For coal, it can depend on the type of coal and firing conditions, while natural gas has efficiency variances around not only loading but also temperature factors. Hence, for the analysis, the following simplified assumptions were used:

(i) Comparisons of the natural gas and coal plant emissions were made against units that did not have emission reduction equipment in the case of NO_2 and SO_2.

(ii) For coal and natural gas base loaded plants, cycles were conducted around a 95% capacity factor with up and down ramping of +/- 5% of capacity. Cycling can be adjusted to occur around another factor by adjusting the Heat Rate factors for each of the charging and discharging inputs per the worksheet heat rate vs. capacity output table.

(iii) ISO related "System-wide" emission outputs were used in calculating the emissions from the flywheel and hydro pumped storage options associated with the losses. This data was taken from EPA eGRID [1] and DOE Energy Information Administration (EIA) [2] databases. System-wide ISO emissions do take emission control technology into account.

(iv) Coal emission factors are typically calculated based on loads of 80% or greater. Although the emissions generated at a given heat rate or efficiency are influenced by additional factors related to fuel type, the actual plant output has a more significant impact on the overall emissions, which allows the use of the simple calculation.

(v) Because the data was taken for one cycle and extrapolated over an entire year for the base load configurations, the focus of the model is on operations during that single cycle.

(vi) For coal and natural gas-fired generation, KEMA's research found that frequency regulation results in increased fuel consumption on the order of 0.5 to 1.5%. For this study 0.7% is used as the increased fuel consumption. This finding is supported from estimates made by a U.S. DOE National Lab, information obtained from ISOs, and from a European study [9, 10] that evaluated electricity producers to determine whether power plants providing frequency regulation had an increase in fuel consumption and maintenance requirements. This effect was reflected in the model.

3.2 Flywheel Charging and Discharging Cycles

For frequency regulation, the first general assumptions that were used were the number of cycles that occurred for each day. A cycle was defined as 15 minute ramp up or charging period, a 15 minute ramp down or discharging period, and 30 minutes of maintaining steady state or normal operations. For a complete day, 24 cycles were examined. The model uses a build-up approach that focuses on a single cycle, then extrapolates that data into a single day, a single year, and finally to a 20-year lifetime. Partial charges and discharge cycles were not considered. The flywheel was modeled as a system and emissions where calculated for all equipment and operations included in the entire system.

3.3 Flywheel Operation

For the flywheel to operate in frequency regulation mode, four separate modes of operation were taken into account. These include: ramp-up (charging), ramp down (discharging), steady state period where the voltage level is being maintained in the flywheel, and an accommodation for the percentage of time when the flywheel system is unavailable for frequency regulation because it has run out of energy. KEMA utilized Beacon data for this percentage. In the scale power test unit in California, Beacon determined the flywheel was available 98.3% of the time for frequency regulation. Hence, a factor of 1.7% was used to account for the percent of time that the unit was unavailable. The emissions are created during these operating scenarios by the flywheel using power from the grid to make up for the estimated 10% load losses on ramp up and ramp down, 1% energy required to maintain the flywheel, and the remaining unavailability utilization factor.

These idling losses (1%) of the flywheel can be absorbed from the grid or they can be compensated with renewable energy resources (solar or wind plant). In these calculations all flywheel losses are compensated by the generation mix of the specific ISO. Emissions rates used in these calculations use standard area fossil emission factors and "system" average heat rates and reflect the generation mix of the ISO region.

It was estimated that the flywheel system plant is able to provide only regulation during the availability period (assumed 98.3%) and that the overall charge - discharge efficiency of the flywheel is assumed at 80% (10% for ramp-up and 10% for ramp-down).

3.4 Coal-fired Plant Operation

The coal-fired plant emission data is calculated under two scenarios:

a) The first scenario is a base-load operation. Under this scenario, the coal plant is deemed to be a large power plant (400MW), base-loaded, and participating in a steady energy market. Hence, as the plant is considered to be already on-line, the emissions calculations above normal operations only occur when the plant is asked to increased its output (ramp-up) or decrease its output (ramp-down).

Summarizing:

i. A large power plant was used (400 MW) to represent a base-loaded coal plant that would be supplying wholesale energy to the market.

ii. Plant size was selected in order to allow a plant that could supply 20 MW around its rated 95 % capacity.

iii. Heat rates were used from a "general" coal plant without emissions reduction equipment [5]. General estimates of heat rate fluctuations off the 100% operation were obtained through an estimated heat rate curve.

iv. A cycle was determined by a ramp-up, increasing output to the grid, and ramp-down decreasing output of the power plant.

b) A second operating scenario is in "peaker" operation. Under this scenario, the emissions of the coal plant are estimated in a "peaker" operating mode. In a "peaker" operating mode the plant is only operating to participate in the frequency regulation market. In this case, the ramp up and ramp down emissions are calculated, as well as idling emissions, where the emissions for the output while idling are compared against the same output that would have been produced by a plant running at full rated capacity. Data for typical emission rates were taken from the EPA eGRID [1] and DOE EIA [2] databases on ISO emission factors. It is assumed that these plants operate only for a limited time during the day and year.

Summarizing:

i. The power plant operates for a limited number of hours per day (typically 6-12 hours per day). In this calculation 8 hours was used.

ii. A size of 75 MW plant size was assumed in order to allow power plant output to swing from + 20 MW to – 20 MW around an idling situation.

iii. Model assumes plant is in idling model of operation to respond to frequency regulation, emissions for idling condition (supplying power to market) is counted towards emission. Amount of emissions is calculated by comparing the emissions of the idling power plant to that of a power plant providing the equivalent amount of output (MW) while operating at is full rated capacity. The emission of the plant operated at full capacity is used as a plant would otherwise be supplying that power and output to the grid (100% base loaded operation).

iv. Ramp up and ramp down cycles are measured against output swings around the idling capacity of 50%.

v. For peaking plants, a decrease in output of plant has a more dominant effect on the results than the rising heat rate. Ramp-down cycles act as an offset to the ramp-up cycle.

vi. Fuel content for CO_2, SO_2, and NO_x were based on coal power generation data from 2004 EPA eGRID [1], and the 2000 DOE EIA [2] databases for the specific regions examined. (PJM, ISO NE, CA ISO).

3.5 Natural Gas Fired Combustion Turbines

Like the coal-fired power plants, the natural gas turbines are operated in the same modes of operation – Base-load and "Peaker" operation as discussed in the Section 3.4. Heat rate data from a typical Natural Gas fired plant was utilized for the study. As the emission factors for the natural gas plants are lower than for coal, estimated emissions were correspondingly less than those produced by coal-fired plants. Lifetime emissions savings for a flywheel regulation plant replacing a base-load natural gas-fired plant were calculated to be 23-53% for CO_2, depending on the ISO region.

The analysis showed the flywheel to have greater emission than the natural gas plant for SO_2 and NO_x. These differences are accounted from the fact the flywheel creates its emissions indirectly from an average of all generation sources on the system. These system averages were taken from EPA eGRID [1] and DOE EIA [2] databases. This is the main driver to the Natural Gas Power Plant producing less NO_x and SO_2 emissions versus the flywheel-based system.

KEMA believes that a significant amount of frequency regulation is conducted with natural gas combustion turbines. Operation of the base loaded and peaker power plants were similar to the coal units. The main differences between the two technologies are in the size of the efficiency fluctuations and a higher minimum load level used for gas generation compared to coal. The analysis only varied heat rate based on partial loading. Natural gas turbine efficiencies are also typically subject to variations such as temperature. However, for this analysis, only efficiency fluctuations were included.

3.6 Hydro Pump Storage

Pump-storage scenarios were similar to the flywheel scenario insofar as like the flywheel regulation, hydro regulation does not produce emissions directly. The indirect emissions that were calculated were based on the inefficiencies of the system and the extra energy that is required to make up for the losses. The losses associated with ramping up and ramping down are larger than that of the flywheel since the efficiency of a hydro pump storage facility is lower. Thus the overall emissions for hydro pump storage are greater than those for the flywheel. It was estimated that a pump hydro plant is able to provide regulation 100% of time. The overall charge - discharge efficiency of the hydro system was estimated at 70%.

3.7 Assumptions on ISO Generation Mix

The mix of power generation technologies and average system heat rates for fossil-based power generation systems varies across regions in the United States. To obtain a regionally adjusted emissions comparison, system data specific to three Independent System Operator (ISO) regions were examined: PJM (Mid-Atlantic), California ISO (CAISO), and ISO New England (ISO NE). The year 2004 data in the EPA eGRID [1] and year 2000 DOE EIA [2] databases were used to assume the different generation mixes in the different ISOs investigated. Model calculations assumed typical heat rate and efficiency data for each type of generation.

The flywheel emissions were compared to the emissions of the generators that are currently actively bidding into the frequency regulation ancillary services market. These are mainly Natural Gas, Coal and Oil power plants. A summary of the year 2004 generation mixes for each of the ISO territories used in the analysis is shown below in Table 4.

Table 4: Assumed Generation Mix in Different ISOs

Territory	Fuel Type	Fuel Mix (%)
	Coal Power Plant	58.9%
	Natural Gas	5.4%
PJM	Oil	2.5%
	Nuclear	31.0%
	Hydro	1.1%
	Wind	0.1%
	Biomass	.9%
	Coal Power Plant	15.7%
	Natural Gas	38.4%
ISO-NE	Oil	8.2%
	Nuclear	28.0%
	Hydro	5.0%
	Wind	0%
	Non-Hydro Renew	4.7%
	Coal Power Plant	6.9%
	Natural Gas	49.3%
CA ISO	Oil	.8%
	Nuclear	15.9%
	Hydro	16.4%
	Wind	2.2%
	Biomass	3.2%
	Geothermal	5.2%

4. Developed Emissions Evaluation Tool

4.1 Description of Emission Tool

To support the evaluation, a detailed model was developed to compare the emissions of CO_2, SO_2 and NO_x for one of Beacon Power's planned 20 MW flywheel plants versus the three major types of conventional power generation technologies used today to perform frequency regulation. A spreadsheet based tool has been developed as part of this phase of the project. The tool has variable inputs on the different assumptions, discussed above. These inputs are used to calculate the emissions comparison per ISO region.

4.2 Variable Inputs to Emission Tool

An example of the different variable inputs is shown in Table 5. The input variables are shown for the flywheel. Similar input tabs are used for the different generator types. The table shows how the operation of the application is defined and where losses are accounted for during operation. In the model, these inputs are set up for each of the technologies being analyzed.

Table 5: Variable Input Page for Flywheel

Variables		
Max Cycles per day	24	cycles
Size	20,000	kW
Heat Rate(PJM)	10,128	btu/kWh
Charge/Discharge Time	0.25	hr
Total System Losses	14%	Percentage
Percentage Regulation Compliance	98.3%	Percentage
Cycle Time with No Load	0.5	hr
Solar System Providing No Load Power Toggle	No	

4.3 Output of Emission Comparison Tool

Table 6 is a summary of the emissions data obtained from modeling the operation of the Beacon Power flywheels against the other options for frequency regulation - a base-loaded coal plant, a "peaker" coal plant, base-loaded natural gas plant, a "peaker" gas plant and hydro pump storage are compared with the flywheel emissions output.

Table 6: Comparison of Emissions Output Data

Comparison	CO_2				SO_2				NOx			
	Per Cycle	Per Day	Per Year (tons)	Per Lifetime (tons)	Per Cycle	Per Day	Per Year (tons)	Per Lifetime (tons)	Per Cycle	Per Day	Per Year (tons)	Per Lifetime (tons)
PJM	lbs		tons		lbs		tons		lbs		tons	
Fly Wheel	1,704	40,889	7,462	149,246	11	263	48	962	3	71	13	259
Coal Baseload	3,526	84,615	15,442	308,845	24	572	104	2,088	6	149	27	543
Coal Peaker	3,814	168,907	30,825	616,509	26	1,454	265	5,307	7	378	69	1,381
Natural Gas Baseload	2,225	53,402	9,746	194,918	0	0	0	0	1	29	5	105
Natural Gas Peaker	1,188	61,490	11,222	224,439	0	0	0	0	1	42	8	154
Pump Storage	2,312	55,479	10,125	202,497	15	357	65	1,305	4	96	18	351
ISO-NE	lbs		tons		lbs		tons		lbs		tons	
Fly Wheel	1,218	29,232	5,335	106,697	3	74	14	270	1	32	6	115
Coal Baseload	3,479	83,496	15,238	304,759	15	356	65	1,300	5	114	21	416
Coal Peaker	3,764	166,672	30,418	608,354	16	905	165	3,303	3	271	50	990
Natural Gas Baseload	2,253	54,071	9,868	197,359	0	0	0	0	1	16	3	58
Natural Gas Peaker	1,203	62,260	11,362	227,249	0	0	0	0	0	23	4	85
Pump Storage	1,653	39,662	7,238	144,766	4	100	18	367	2	43	8	157
CA ISO	lbs		tons		lbs		tons		lbs		tons	
Fly Wheel	1,040	24,953	4,554	91,079	1	23	4	63	1	18	3	64
Coal Baseload	3,676	88,222	16,100	322,009	13	302	55	1,103	6	137	25	499
Coal Peaker	3,977	176,106	32,139	642,789	14	768	140	2,803	6	348	63	1,269
Natural Gas Baseload	2,221	53,297	9,727	194,534	0	0	0	0	1	22	4	80
Natural Gas Peaker	1,186	61,369	11,200	223,997	0	0	0	0	0	32	6	118
Pump Storage	1,411	33,857	6,179	123,577	1	23	4	85	1	24	4	87

These evaluation results are also summarized for each of the ISO territories in Table 7, Table 8, and Table 9 for the 20 year life cycle of the application.

Table 7: Emissions Comparison for PJM

Flywheel Emission Savings Over 20-year Life: PJM

	Coal		Natural Gas		Pumped Hydro
	Baseload	Peaker	Baseload	Peaker	
CO2					
Flywheel	149,246	149,246	149,246	149,246	149,246
Alternate Gen.	308,845	616,509	194,918	224,439	202,497
Savings (Flywheel)	159,599	467,263	45,672	75,193	53,252
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Savings (Flywheel)	1,127	4,345	-962	-962	343
Percent Savings	54%	82%	n/a	n/a	26%
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Flywheel	259	259	259	259	259
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Savings (Flywheel)	284	1,122	-154	-105	92
Percent Savings	52%	81%	-148%	-68%	26%

Table 8: Emissions Comparisons for CAISO

Flywheel Emission Savings Over 20-year Life: CA-ISO

	Coal		Natural Gas		Pumped Hydro
	Baseload	Peaker	Baseload	Peaker	
CO2					
Flywheel	91,079	91,079	91,079	91,079	91,079
Alternate Gen.	322,009	608,354	194,534	223,997	123,577
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Percent Savings	72%	85%	53%	59%	26%
SO2					
Flywheel	63	63	63	63	63
Alternate Gen.	1,103	2,803	0	0	85
Savings (Flywheel)	1,041	2,741	-63	-63	23
Percent Savings	94%	98%	n/a	n/a	27%
NOx					
Flywheel	64	64	64	64	64
Alternate Gen.	499	1,269	80	118	87
Savings (Flywheel)	435	1,205	16	54	23
Percent Savings	87%	95%	20%	46%	26%

Table 9: Emissions Comparisons for ISO-NE

Flywheel Emission Savings Over 20-year Life: ISO-NE	Coal		Natural Gas		Pumped Hydro
	Baseload	Peaker	Baseload	Peaker	
CO2					
Flywheel	106,697	106,697	106,697	106,697	106,697
Alternate Gen.	304,759	608,354	197,359	227,249	144,766
Savings (Flywheel)	198,062	501,657	90,662	120,552	38,070
Percent Savings	65%	82%	46%	53%	26%
SO2					
Flywheel	270	270	270	270	270
Alternate Gen.	1,300	3,303	0	0	367
Savings (Flywheel)	1,030	3,033	-270	-270	96
Percent Savings	79%	92%	n/a	n/a	26%
NOx					
Flywheel	115	115	115	115	115
Alternate Gen.	416	990	58	85	157
Savings (Flywheel)	301	875	-58	-31	41
Percent Savings	72%	88%	-101%	-36%	26%

4.4 Discussions of the Emission Comparison Results

The emissions comparisons estimates showed highly favorable results for the flywheel for reduction of CO_2. The developed model and analysis shows that the flywheel-based frequency regulation can be expected to create significantly less CO_2 for all of the generation technologies in every region, as well as less NO_x emissions for all technologies in the CAISO region.

Lifetime CO_2 savings for a flywheel-based regulation plant displacing a coal-fired plant in the PJM Interconnect area were estimated to be 159,599 tons for a base loaded coal plant and 467,263 tons for a peaker coal plant. This translates to projected reductions of 52% and 76%, respectively. In the ISO NE region, CO_2 reduction versus base loaded and peaker coal plants were projected to be 65% and 82%, respectively.

Lifetime CO_2 savings for a flywheel-based regulation plant displacing a base loaded natural gas-fired plant in California were estimated to be 103,455 tons, while CO_2 savings for a peaker gas plant were 132,917 tons. This translates to a projected savings of 53% and 59% in CO_2 emissions, respectively.

Lifetime CO_2 savings for a flywheel-based regulation plant displacing a pumped hydro plant were 26% in all three regions.

The flywheel system resulted in slightly higher indirect emissions of NO_x and SO_2 in PJM and ISO NE for gas-fired generation. This is because PJM and ISO NE's generation mix includes coal-fired plants as well as the low SO_2 emissions from Natural Gas power plants. The make-up electricity used by the flywheel and hydro systems reflects higher NO_x and SO_2 emissions from electricity generated in those areas.

5. Conclusions

In this report, KEMA compared the emissions from different frequency regulation generator technologies that actively participate in the ancillary services market, with the equivalent emissions associated with a 20 MW flywheel plant. A detailed model was developed to compare the emissions of CO_2, SO_2 and NO_x for a Beacon Power flywheel plant versus three types of commercially available power generation technologies used in the market to perform frequency regulation ancillary services.

The generation technologies compared included a typical coal-fired power plant, natural gas combustion turbine, and pumped storage hydro system. Emissions from the coal and natural gas-fired generation technologies result directly from their operation because they burn fossil fuels. In contrast, emissions for the flywheel and pumped hydro energy storage systems occur indirectly because they use some electricity from the grid to compensate for energy losses during operation.

The mix of power generation technologies and average system heat rates for fossil-based power generation systems varies across regions in the United States. To obtain a regionally adjusted emissions comparison, system data specific to three Independent System Operator (ISO) regions were examined: PJM (Mid-Atlantic), California ISO (CAISO), and ISO New England (ISO NE). Data for each of these ISOs was extracted from the most recent DOE EIA, and EPA eGrid databases. Model calculations assumed typical heat rate and efficiency data for each type of generation.

For coal and natural gas-fired generation, KEMA's research found that frequency regulation results in increased fuel consumption on the order of 0.5 to 1.5%. In this study 0.7% increased fuel consumption is used.

Based on the above data, model analysis showed that flywheel-based frequency regulation can be expected to produce significantly less CO_2 for all three regions and all of the generation technologies, as well as less NO_x and SO_2 emissions for all technologies in the CAISO region. The flywheel system resulted in slightly higher indirect emissions of NO_x and SO_2 in PJM and ISO NE for gas-fired generation. This effect was greatest in PJM because it has proportionally more coal-fired plants than ISO NE.

When the flywheel system was compared against "peaker" plants for the same fossil generation technologies, the emissions advantages of the flywheel system were even greater.

6. Recommendations

- All the data of this study was based on publicly available data from DOE, EPA and the different ISO sites. Some of the data may be dated in terms of the generation mix and generating efficiencies and heat rates. These results should be validated with direct ISO involvement in a future study.

- The assumed generation data is of a generic plant. It is thus limited in the details of specific frequency regulation plant efficiencies under different operating scenarios. It is proposed that a more in-depth analysis is performed based on specific coal or gas-fired generators. This should be done to calculate the specific emission savings that the flywheel installation can achieve at a specific installation in a certain ISO region.

- The frequency regulation control signal from a specific ISO could not be integrated into the current simplistic model. When a specific site is selected for frequency regulation, it is recommended to use specific generation data and integrate the relevant ISO frequency regulation control signal. This will be valuable to investigate the impact of partial discharge cycles on the lifetime emissions savings of the flywheel system compared to other generation technologies.

- The flywheel system has a much faster dynamic response compared to other frequency regulation generation technologies. The faster response or ramp-rate of the flywheel system can provide better frequency regulation results compared to conventional generation units. For comparison this improved performance could not be evaluated.

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ATTACHMENT 4

Power-Electronic Systems for the Grid Integration of Renewable Energy Sources: A Survey

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***Abstract*—The use of distributed energy resources is increasingly being pursued as a supplement and an alternative to large conventional central power stations. The specification of a power-electronic interface is subject to requirements related not only to the renewable energy source itself but also to its effects on the power-system operation, especially where the intermittent energy source constitutes a significant part of the total system capacity. In this paper, new trends in power electronics for the integration of wind and photovoltaic (PV) power generators are presented. A review of the appropriate storage-system technology used for the integration of intermittent renewable energy sources is also introduced. Discussions about common and future trends in renewable energy systems based on reliability and maturity of each technology are presented.**

***Index Terms*—Direct drives, doubly fed induction generator (DFIG), flywheel, hydrogen, multilevel converter topologies, supercapacitors, superconducting magnetic energy storage (SMES), wind diesel.**

I. INTRODUCTION

THE INCREASING number of renewable energy sources and distributed generators requires new strategies for the operation and management of the electricity grid in order to maintain or even to improve the power-supply reliability and quality. In addition, liberalization of the grids leads to new management structures, in which trading of energy and power is becoming increasingly important. The power-electronic technology plays an important role in distributed generation and in integration of renewable energy sources into the electrical grid, and it is widely used and rapidly expanding as these applications become more integrated with the grid-based systems.

During the last few years, power electronics has undergone a fast evolution, which is mainly due to two factors. The first one is the development of fast semiconductor switches that are capable of switching quickly and handling high powers. The second factor is the introduction of real-time computer controllers that can implement advanced and complex control algorithms. These factors together have led to the development of cost-effective and grid-friendly converters.

In this paper, new trends in power-electronic technology for the integration of renewable energy sources and energy-storage systems are presented. This paper is organized as follows. In Section II, we describe the current technology and future trends in variable-speed wind turbines. Wind energy has been demonstrated to be both technically and economically viable. It is expected that current developments in gearless energy transmission with power-electronic grid interface will lead to a new generation of quiet, efficient, and economical wind turbines. In Section III, we present power-conditioning systems used in grid-connected photovoltaic (PV) generation plants. The continuously decreasing prices for the PV modules lead to the increasing importance of cost reduction of the specific PV converters.

Energy storage in an electricity generation and supply system enables the decoupling of electricity generation from demand. In other words, the electricity that can be produced at times of either low-demand low-generation cost or from intermittent renewable energy sources is shifted in time for release at times of high-demand high-generation cost or when no other generation is available. Appropriate integration of renewable energy sources with storage systems allows for a greater market penetration and results in primary energy and emission savings. In Section IV, we present research and development trends in energy-storage systems used for the grid integration of intermittent renewable energy sources.

II. WIND-TURBINE TECHNOLOGY

A. Variable-Speed Wind Turbines

Wind energy has matured to a level of development where it is ready to become a generally accepted utility generation technology. Wind-turbine technology has undergone a dramatic transformation during the last 15 years, developing from a fringe science in the 1970s to the wind turbine of the 2000s using the latest in power electronics, aerodynamics, and mechanical drive train designs [1], [2]. In the last five years, the world wind-turbine market has been growing at over 30% a year, and wind power is playing an increasingly important role in electricity generation, especially in countries such as Germany and Spain. The legislation in both countries favors the continuing growth of installed capacity. Wind power is quite

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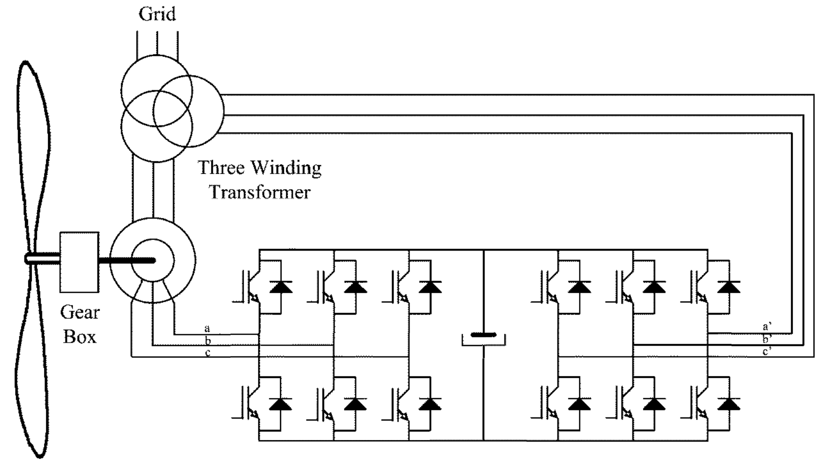


Fig. 1. Single doubly fed induction machine with two fully controlled ac–dc power converters.

different from the conventional electricity generation with synchronous generators. Further, there are differences between the different wind-turbine designs available on the market. These differences are reflected in the interaction of wind turbines with the electrical power system. An understanding of this is, therefore, essential for anyone involved in the integration of wind power into the power system.

Moreover, a new technology has been developed in the wind-power market introducing variable-speed working conditions depending on the wind speed in order to optimize the energy captured from the wind. The advantages of variable-speed turbines are that their annual energy capture is about 5% greater than the fixed-speed technology, and that the active and reactive powers generated can be easily controlled. There is also less mechanical stress, and rapid power fluctuations are scarce because the rotor acts as a flywheel (storing energy in kinetic form). In general, no flicker problems occur with variable-speed turbines. Variable-speed turbines also allow the grid voltage to be controlled, as the reactive-power generation can be varied. As disadvantages, variable-speed wind turbines need a power converter that increases the component count and make the control more complex. The overall cost of the power electronics is about 7% of the whole wind turbine.

B. Current Wind-Power Technology

Variable-speed wind turbines have progressed dramatically in recent years. Variable-speed operation can only be achieved by decoupling the electrical grid frequency and mechanical rotor frequency. To this end, power-electronic converters are used, such as an ac–dc–ac converter combined with advanced control systems.

1) Variable-Speed Concept Utilizing Doubly Fed Induction Generator (DFIG): In a variable-speed turbine with DFIG [3], [4], the converter feeds the rotor winding, while the stator winding is connected directly to the grid. This converter, thus decoupling mechanical and electrical frequencies and making variable-speed operation possible, can vary the electrical rotor frequency. This turbine cannot operate in the full range from zero to the rated speed, but the speed range is quite sufficient. This limited speed range is caused by the fact that a converter that is considerably smaller than the rated power of the machine is used. In principle, one can say that the ratio between the size of the converter and the wind-turbine rating is half of the rotor-speed span. In addition to the fact that the converter is smaller, the losses are also lower. The control possibilities of the reactive power are similar to the full power-converter system. For instance, the Spanish company Gamesa supplies this kind of variable-speed wind turbines to the market.

The forced switched power-converter scheme is shown in Fig. 1. The converter includes two three-phase ac–dc converters linked by a dc capacitor battery. This scheme allows, on one hand, a vector control of the active and reactive powers of the machine, and on the other hand, a decrease by a high percentage of the harmonic content injected into the grid by the power converter.

Vestas and Nordic Windpower supply a variation of this design, which is the semivariable-speed turbine, in which the rotor resistance of the squirrel cage generator can be varied instantly using fast power electronics. So far, Vestas alone has succeeded in commercializing this system under the trade name OptiSlip. A number of turbines, ranging from 600 kW to 2.75 MW, have now been equipped with this system, which allows transient rotor speed increases of up to 10% of the nominal value. In that case, the variable-speed conditions are achieved dissipating the energy within a resistor placed in the rotor, as shown in Fig. 2. Using that technology, the efficiency of the system decreases when the slip increases, and the speed control is limited to a narrow margin. This scheme includes the power converter and the resistors in the rotor. Trigger signals to the power switches are accomplished by optical coupling.

2) Variable-Speed Concept Utilizing Full-Power Converter: In this concept, the generator is completely decoupled from the grid [5]. The energy from the generator is rectified to a dc link and after is converted to a suitable ac energy for the grid. The majority of these wind turbines are equipped with a multipole synchronous generator, although it is quite possible (but rather rare) to use an induction generator and a gearbox. There are several benefits of removing the gearbox: reduced losses, lower costs due to the elimination of this expensive component, and increased reliability due to the elimination of rotating mechanical components. Enercon supplies such technology.

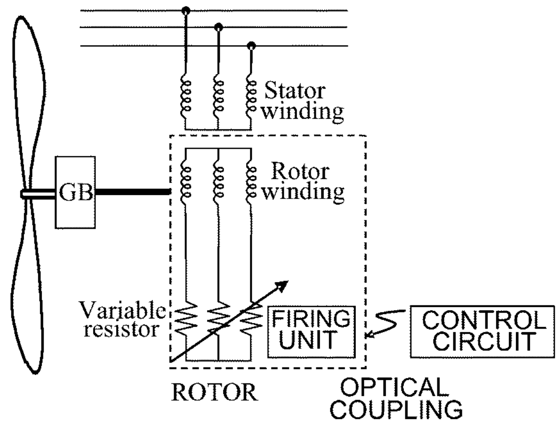


Fig. 2. Single doubly fed induction machine controlled with slip power dissipation in an internal resistor.

Fig. 3 shows the scheme of a full power converter for a wind turbine. The machine-side three-phase converter works as a driver controlling the torque generator, using a vector control strategy. The grid-side three-phase converter permits wind-energy transfer into the grid and enables to control the amount of the active and reactive powers delivered to the grid. It also keeps the total-harmonic-distortion (THD) coefficient as low as possible, improving the quality of the energy injected into the public grid. The objective of the dc link is to act as energy storage, so that the captured energy from the wind is stored as a charge in the capacitors and may be instantaneously injected into the grid. The control signal is set to maintain a constant reference to the voltage of the dc link V_{dc}. An alternative to the power-conditioning system of a wind turbine is to use a synchronous generator instead of an induction one and to replace a three-phase converter (connected to the generator) by a three-phase diode rectifier and a chopper, as shown in Fig. 4. Such choice is based on the low cost as compared to an induction generator connected to a voltage-source inverter (VSI) used as a rectifier. When the speed of the synchronous generator alters, the voltage value on the dc side of the diode rectifier will change. A step-up chopper is used to adapt the rectifier voltage to the dc-link voltage of the inverter. When the inverter system is analyzed, the generator/rectifier system can be modeled as an ideal current source. The step-up chopper used as a rectifier utilizes a high switching frequency, so the bandwidth of these components is much higher than the bandwidth of the generator. Controlling the inductance current in the step-up converter can control the machine torque and, therefore, its speed. The Spanish Company MADE has marketed that design.

3) Semiconductor-Device Technology: Improvements in the performance and reliability of power-electronic variable frequency drives for wind-turbine applications have been directly related to the availability of power semiconductor devices with better electrical characteristics and lower prices because the device performance determines the size, weight, and cost of the entire power electronics used as interfaces in wind turbines.

The insulated gate bipolar transistor (IGBT) is now the main component for power electronics and also for wind-turbine applications. They are now mature technology turn-on components adapted to a very high power (6 kV–1.2 kA), and they are in competition with gate turn-off thyristors (GTOs) for high-power applications [6].

Recently, the integrated gated control thyristor (IGCT) has been developed as a mechanical integration of a GTO plus a delicate hard drive circuit that transforms the GTO into a modern high-performance component with a large safe operation area (SOA), lower switching losses, and a short storage time [7]. The comparison between IGCT and IGBT for frequency converters that are used, especially in wind turbines, is explained below.

1) IGBTs have higher switching frequency than IGCTs, so they introduce less distortion in the grid.
2) IGCTs are made like disk devices. They have to be cooled with a cooling plate by electrical contact on the high-voltage side. This is a problem because high electromagnetic emission will occur. Another point of view is the number of allowed load cycles. Heating and cooling the device will always bring mechanical stress to the silicon chip, and it can be destroyed. This is a serious problem, especially in wind-turbine applications. On the other hand, IGBTs are built like modular devices. The silicon is isolated to the cooling plate and can be connected to ground for low electromagnetic emission even with higher switching frequency. The base plate of this module is made of a special material that has exactly the same thermal behavior as silicon, so nearly no thermal stress occurs. This increases the lifetime of the device by ten folds approximately.
3) The main advantage of IGCTs versus IGBTs is that they have a lower ON-state voltage drop, which is about 3.0 V for a 4500-V device. In this case, the power dissipation due to a voltage drop for a 1500-kW converter will be 2400 W per phase. On the other hand, in the case of IGBT, the voltage drop is higher than IGCTs. For a 1700-V device having a drop of 5 V, the power dissipation due to the voltage drop for a 1500-kW condition will be 5 kW per phase.

In conclusion, with the present semiconductor technology, IGBTs present better characteristics for frequency converters in general and especially for wind-turbine applications.

C. Grid-Connection Standards for Wind Farms

1) Voltage Fault Ride-Through Capability of Wind Turbines: As the wind capacity increases, network operators have to ensure that consumer power quality is not compromised. To enable a large-scale application of the wind energy without compromising the power-system stability, the turbines should stay connected and contribute to the grid in case of a disturbance such as a voltage dip. Wind farms should generate like conventional power plants, supplying active and reactive powers for frequency and voltage recovery, immediately after the fault occurred.

Thus, several utilities have introduced special grid-connection codes for wind-farm developers, covering reactive-power control, frequency response, and fault ride through,

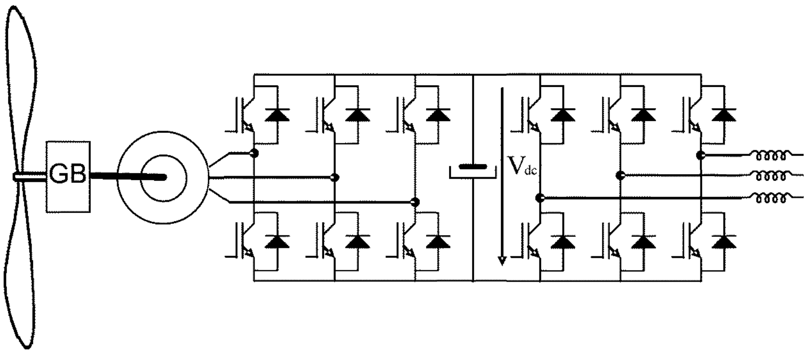


Fig. 3. Double three-phase VSI.

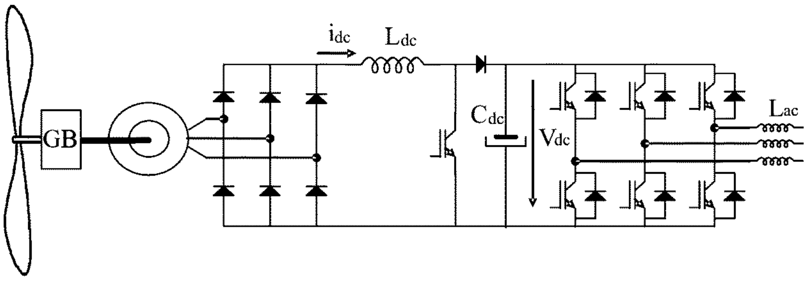


Fig. 4. Step-up converter in the rectifier circuit and full power inverter topology used in wind-turbine applications.

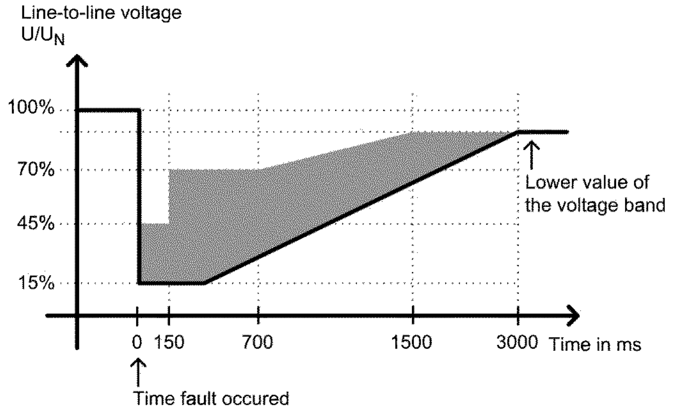


Fig. 5. E.ON Netz requirements for fault ride-through capability of wind turbines connected to the grid.

especially in places where wind turbines provide for a significant part of the total power. Examples are Spain, Denmark, and part of Northern Germany.

The correct interpretation of these codes is crucial for wind-farm developers, manufacturers, and network operators. They define the operational boundary of a wind turbine connected to the network in terms of frequency range, voltage tolerance, power factor, and fault ride through. Among all these requirements, fault ride through is regarded as the main challenge to the wind-turbine manufacturers. Although the definition of fault ride through varies, the German Transmission and Distribution Utility (E.ON) regulation is likely to set the standard [8]. This stipulates that a wind turbine should remain stable and connected during the fault while voltage at the point of connection drops to 15% of the nominal value (i.e., a drop of 85%) for a period of 150 ms (see Fig. 5).

Only when the grid voltage drops below the curve, the turbine is allowed to disconnect from the grid. When the voltage is in the shaded area, the turbine should also supply a reactive power to the grid in order to support the grid-voltage restoration.

2) Power-Quality Requirements for Grid-Connected Wind Turbines: The grid interaction and grid impact of wind turbines have been focused on during the past few years. The reason behind this interest is that wind turbines are among the utilities considered to be potential sources of bad power quality. Measurements show that the power-quality impact of wind turbines has been improved in recent years. Especially, variable-speed wind turbines have some advantages concerning flicker. But, a new problem arose with variable-speed wind turbines. Modern forced-commutated inverters used in variable-speed wind turbines produce not only harmonics but also interharmonics.

The International Electrotechnical Commission (IEC) initiated the standardization on the power quality for wind turbines in 1995 as part of the wind-turbine standardization in TC88, and ultimately 1998 IEC issued a draft IEC-61400-21 standard for “power-quality requirements for Grid Connected Wind Turbines” [9]. The methodology of that IEC standard consists of three analyses. The first one is the flicker analysis. IEC-61400-21 specifies a method that uses current and voltage time series measured at the wind-turbine terminals to simulate the voltage fluctuations on a fictitious grid with no source of voltage fluctuations other than the wind-turbine switching operation. The second one regards switching operations. Voltage and current transients are measured during the switching operations of the wind turbine (startup at cut wind speed and startup at rated wind speed). The last one is the harmonic analysis, which is carried out by the fast Fourier transform (FFT) algorithm. Rectangular windows of eight cycles of fundamental frequency width, with no gap and no overlapping between

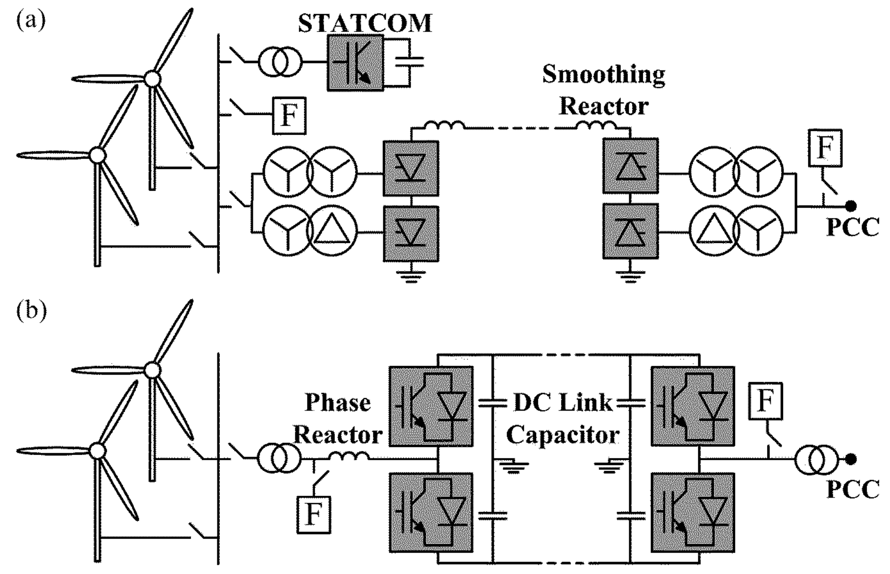


Fig. 6. Two HVDC transmission solutions. (a) Classical LCC-based system with STATCOM. (b) VSC-based system.

successive windows, are applied. Furthermore, the current total THD is calculated up to 50th harmonic order.

Recently, high-frequency (HF) harmonics and interharmonics are treated in the IEC 61000-4-7 and IEC 61000-3-6 [10], [11]. The methods for summing harmonics and interharmonics in the IEC 61000-3-6 are applicable to wind turbines. In order to obtain a correct magnitude of the frequency components, the use of a well-defined window width, according to the IEC 61000-4-7, Amendment 1, is of a great importance, as has been reported in [12]. Wind turbines not only produce harmonics; they also produce interharmonics, i.e., harmonics that are not a multiple of 50 Hz. Since the switching frequency of the inverter is not constant but varies, the harmonics will also vary. Consequently, since the switching frequency is arbitrary, the harmonics are also arbitrary. Sometimes they are a multiple of 50 Hz, and sometimes they are not.

D. Trends in Wind-Power Technology

1) Transmission Technology for the Future—Connecting Wind Generation to the Grid: One of the main trends in wind-turbine technology is offshore installation. There are great wind resources at sea for installing wind turbines in many areas where the sea is relatively shallow. Offshore wind turbines may have slightly more favorable energy balance than onshore turbines, depending on the local wind conditions. In places where onshore wind turbines are typically placed on flat terrain, offshore wind turbines will generally yield some 50% more energy than a turbine placed on a nearby onshore site. The reason is that there is less friction on the sea surface. On the other hand, the construction and installation of a foundation requires 50% more energy than onshore turbines. It should be remembered, however, that offshore wind turbines have a longer life expectancy than onshore turbines, which is around 25–30 years. The reason is that the low turbulence at sea gives lower fatigue loads on the wind turbine.

Conventional heating–ventilation–airconditioning (HVAC) transmission systems are a simple and cost-efficient solution for the grid connection of wind farms. Unfortunately, for offshore wind parks, the distributed capacitance of undersea cables is much higher than that of overhead power lines. This implies that the maximum feasible length and power-transmission capacity of HVAC cables is limited. Grid access technology in the form of high-voltage dc (HVDC) can connect the wind-farm parks to the grid and transmit the power securely and efficiently to the load centers. Looking at the overall system economics, HVDC transmission systems are most competitive at transmission distances over 100 km or power levels of between approximately 200 and 900 MW. The HVDC transmission offers many advantages over HVAC [13].

1) Sending and receiving end frequencies are independent.
2) Transmission distance using dc is not affected by cable charging current.
3) Offshore installation is isolated from mainland disturbances and vice versa.
4) Power flow is fully defined and controllable.
5) Cable power losses are low.
6) Power-transmission capability per cable is higher.

Classical HVDC transmission systems [as shown in Fig. 6(a)] are based on the current source converters with naturally commutated thyristors, which are the so-called line-commutated converters (LCCs). This name originates from the fact that the applied thyristors need an ac voltage source in order to commutate and thus only can transfer power between two active ac networks. They are, therefore, less useful in connection with the wind farms as the offshore ac grid needs to be powered up prior to a possible startup. A further disadvantage of LCC-based HVDC transmission systems is the lack of the possibility to provide an independent control of the active and reactive powers. Furthermore, they produce large amounts of harmonics, which make the use of large filters inevitable.

Voltage-source-converter (VSC)-based HVDC transmission systems are gaining more and more attention not only for the grid connection of large offshore wind farms. Nowadays, VSC-based solutions are marketed by ABB under the name "HVDC

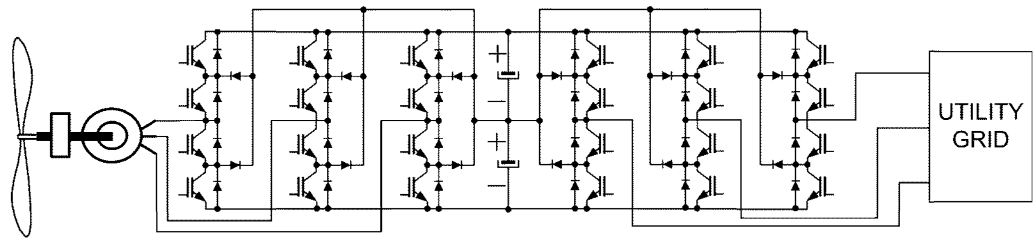


Fig. 7. Multilevel back-to-back converter for a direct connection of a wind turbine to the utility grid.

Light" [14] and by Siemens under the name "HVDC Plus." Fig. 6(b) shows the schematic of a VSC-based HVDC transmission system. This comparatively new technology (with first commercial installation in 1999) has only become possible by the development of the IGBTs, which can switch off currents. This means that there is no need for an active commutation voltage. Therefore, VSC-based HVDC transmission does not require a strong offshore or onshore ac network and can even start up against a dead network (black-start capability). But, VSC-based systems have several other advantages. The active and reactive powers can be controlled independently, which may reduce the need for reactive-power compensation and can contribute to the stabilization of the ac network at their connection points [15].

2) High-Power Medium-Voltage Converter Topologies: In order to decrease the cost per megawatt and to increase the efficiency of the wind-energy conversion, nominal power of wind turbines has been continuously growing in the last years [16].

The different proposed multilevel-converter topologies can be classified into the following five categories [17]:

1) multilevel configurations with diode clamps;
2) multilevel configurations with bidirectional switch interconnection;
3) multilevel configurations with flying capacitors;
4) multilevel configurations with multiple three-phase inverters;
5) multilevel configurations with cascaded single-phase H-bridge inverters.

A common feature of the five different topologies of multilevel converters is that, in theory, all the topologies may be constructed to have an arbitrary number of levels, although in practice, some topologies are easier to realize than others.

As the ratings of the components increase and the switching and conducting properties improve, the advantages of applying multilevel converters become more and more evident. In recent papers, the reduced content of harmonics in the input and output voltages is highlighted together with the reduced electromagnetic interference (EMI) [18]. Moreover, the multilevel converters have the lowest demands for the input filters or alternatively reduced number of commutations [19]. For the same harmonic performance as a two-level converter, the switching frequency of a multilevel converter can be reduced to 25% that results in the reduction of the switching losses [20]. Even though the conducting losses are higher in the multilevel converter, the overall efficiency depends on the ratio between the switching and the conducting losses.

The most commonly reported disadvantage of the multilevel converters with split dc link is the voltage unbalance between the capacitors that integrate it. Numerous hardware and software solutions are reported: the first one needs additional components that increase the cost of the converter and reduce its reliability; the second one needs enough computational capacity to carry out the modulation signals. Recent papers illustrate that the balance problem can be formulated in terms of the model of the converter, and this formulation permits solving the balancing problem directly modifying the reference voltage with a relatively low computational burden [21], [22].

Trends on wind-turbine market are to increase the nominal power (some megawatts) and due to the voltage and current ratings. This makes the multilevel converter suitable for modern high-power wind-turbine applications. The increase of voltage rating allows for connection of the converter of the wind turbine directly to the wind-farm distribution network, avoiding the use of a bulky transformer [23] (see Fig. 7). The main drawback of some multilevel topologies is the necessity to obtain different dc-voltage independent sources needed for the multilevel modulation. The use of low-speed permanent-magnet generators that have a large number of poles allows obtaining the dc sources from the multiple wounds of this electrical machine, as can be seen in Fig. 8. In this case, the power-electronic building block (PEBB) can be composed of a rectifier, a dc link, and an H-bridge. Another possibility is to replace the rectifier by an additional H-bridge. The continuous reduction of the cost per kilowatt of PEBBs is making the multilevel cascaded topologies to be the most commonly used by the industrial solutions.

3) Direct-Drive Technology for Wind Turbines: Direct-drive applications are on increase because the gearbox can be eliminated. As compared to a conventional gearbox-coupled wind-turbine generator, a direct-drive generator has reduced the overall size, has lower installation and maintenance cost, has a flexible control method and quick response to wind fluctuations, and load variation. For small wind turbine, permanent-magnet synchronous machines are more popular because of their higher efficiency, high-power density, and robust rotor structure as compared to induction and synchronous machines. A number of alternative concepts have been proposed for direct-drive electrical generators for use in grid-connected or standalone wind turbines. In [24], the problem to adapt a standard permanent-magnet synchronous machine to a direct-drive application is presented. A complete design of a low-speed direct-drive permanent-magnet generator for wind application is depicted in [25] and [26].

A new trend that is very popular for propulsion systems applications is to use an axial flux machine [27]. These new

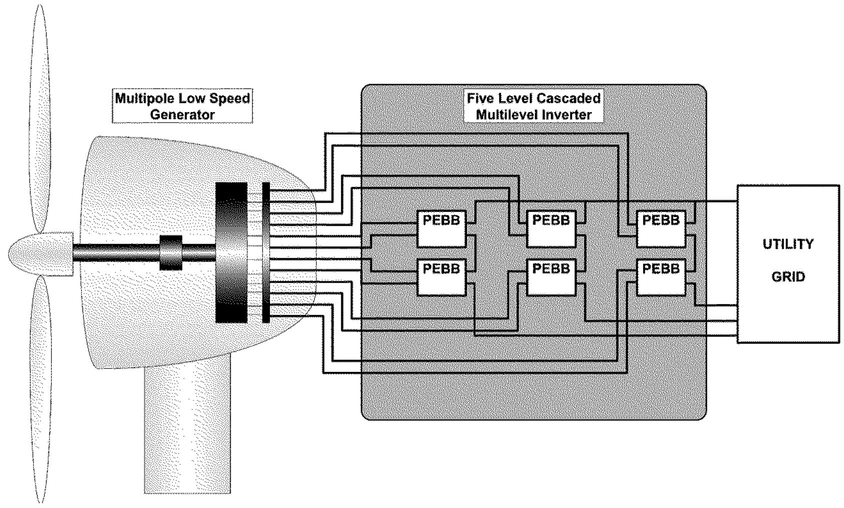


Fig. 8. Five-level cascaded multilevel converter connected to a multipole low-speed wind-turbine generator.

machines are applied in small-scale wind and water-turbine direct-drive generators because higher torque density can be obtained in a more simple and easy way.

4) Future Energy-Storage Technologies Applied in Wind Farms: Energy-storage systems can potentially improve the technical and economic attractiveness of wind power, particularly when it exceeds about 10% of the total system energy (about 20%–25% of the system capacity). The storage system in a wind farm will be used to have a bulk power storage from wind during the time-averaged 15-min periods of high availability and to absorb or to inject energy over shorter time periods in order to contribute to the grid-frequency stabilization.

Several kinds of energy-storage technologies are being applied in wind farms. For wind-power application, the flow (zinc bromine) battery system offers the lowest cost per energy stored and delivered. The zinc–bromine battery is very different in concept and design from the more traditional batteries such as the lead–acid battery. The battery is based on the reaction between two commonly available chemicals: zinc and bromine. The zinc–bromine battery offers two to three times higher energy density (75–85 W · h per kilogram) along with the size and weight savings over the present lead/acid batteries. The power characteristics of the battery can be modified for selected applications. Moreover, zinc–bromine battery suffers no loss of performance after repeated cycling. It has a great potential for renewable energy applications [28].

As the wind penetration increases, the hydrogen options become most economical. Also, sales of hydrogen as a vehicle fuel are more lucrative than reconverting the hydrogen back into electricity. Industry is developing low-maintenance electrolysers to produce hydrogen fuel. Because these electrolysers require a constant minimum load, wind turbines must be integrated with grid or energy systems to provide power in the absence of wind [28].

Electrical energy could be produced and delivered to the grid from hydrogen by a fuel cell or a hydrogen combustion generator. The fuel cell produces power through a chemical reaction, and energy is released from the hydrogen when it reacts with the oxygen in the air. Also, wind electrolysis promises to establish new synergies in energy networks. It will be possible to gradually supply domestic-natural-gas infrastructures, as reserves diminish, by feeding hydrogen from grid-remote wind farms into natural-gas pipelines. Fig. 9 shows a variable-speed wind turbine with a hydrogen storage system and a fuel-cell system to reconvert the hydrogen to the electrical grid.

III. PV TECHNOLOGY

This section focuses on the review of the recent developments of power-electronic converters and the state of the art of the implemented PV systems. PV systems as an alternative energy resource or an energy-resource complementary in hybrid systems have been becoming feasible due to the increase of research and development work in this area. In order to maximize the success of the PV systems, a high reliability, a reasonable cost, and a user-friendly design must be achieved in the proposed PV topologies. Several standards given by the utility companies must be obeyed in the PV-module connection. Nowadays, the standards EN61000-3-2 [29], IEEE1547 [30], and the U.S. National Electrical Code (NEC) 690 [31], and the future international standard (still a Committee Draft for Vote-CDV) IEC61727 [32] are being considered. These standards deal with issues like power quality, detection of islanding operation, grounding, etc. They define the structure and the features of the present and future PV modules.

A. Market Considerations

Solar-electric-energy demand has grown consistently by 20%–25% per annum over the past 20 years, which is mainly due to the decreasing costs and prices. This decline has been driven by 1) an increasing efficiency of solar cells; 2) manufacturing-technology improvements; and 3) economies of scale. In 2001, 350 MW of solar equipment was sold to add to the solar equipment already generating a clean energy. In 2003, 574 MW of PV was installed. This increased to 927 MW in 2004. The European Union is on track to fulfilling its own target of 3 GW of renewable electricity from PV sources for

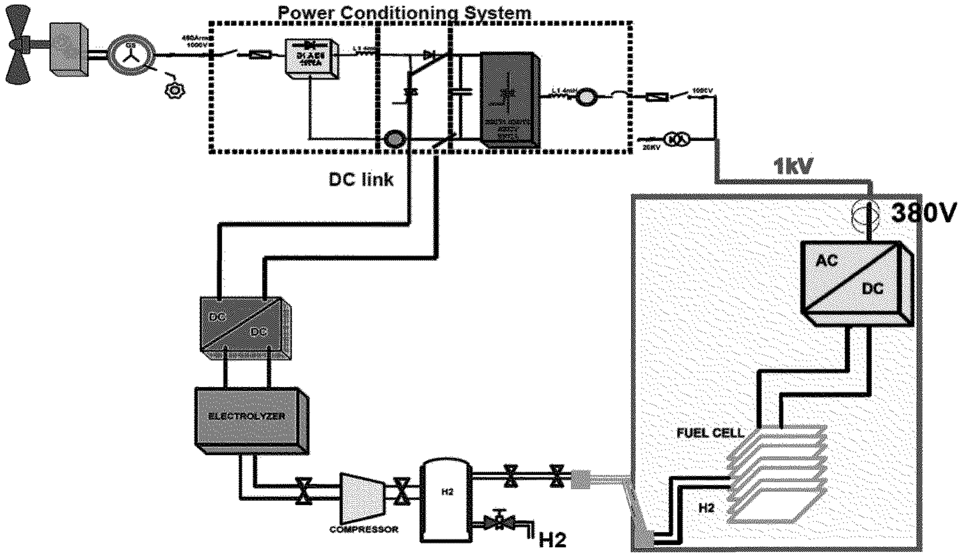


Fig. 9. Variable-speed wind turbine with a hydrogen storage system and a fuel-cell system that reconverts hydrogen to electrical grid.

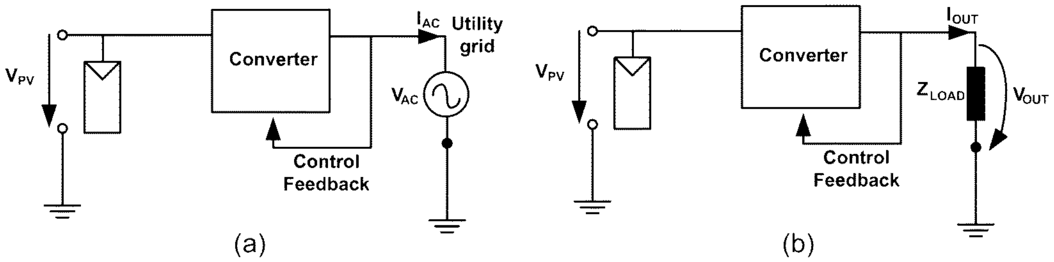


Fig. 10. PV energy applications. (a) Grid-connection application. (b) Power-supply application.

2010, and in Japan, the target is 4.8 GW. If the growth rates of the installation of PV systems between 2001 and 2003 could be maintained in the next years, the target of the European Commission's White Paper for a Community Strategy and Action Plan on Renewable Sources of Energy would already be achieved in 2008. It is important to notice that the PV installation growth-rate curve in the European Union exactly mirrors that of wind power, with a delay of approximately 12 years. This fact predicts a great future for PV systems in the coming years.

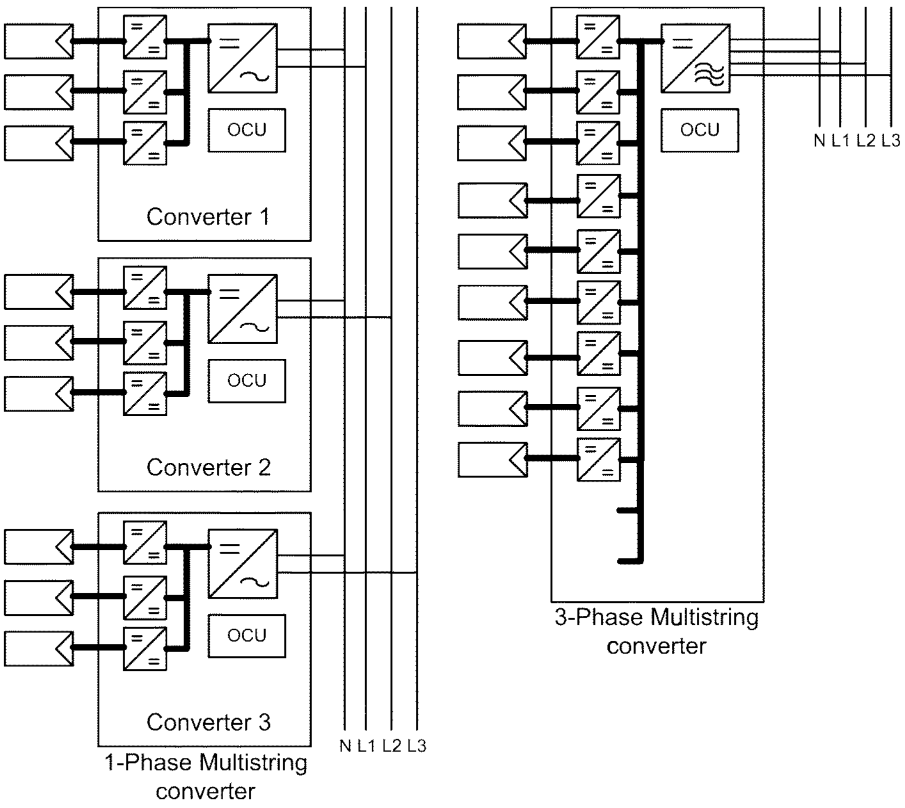
B. Design of PV-Converter Families

An overview of some existing power inverter topologies for interfacing PV modules to the grid is presented. The approaches are further discussed and evaluated in order to recognize the most suitable topologies for future PV converters, and, finally, a conclusion is given.

Due to advances in transistor technology, the inverter topologies have changed from large thyristor-equipped grid-connected inverters to smaller IGBT-equipped ones. These transistors permit to increase the power switching frequency in order to extract more energy and fulfill the connecting standards. One requirement of standards is that the inverters must also be able to detect an islanding situation and take appropriate measures in order to protect persons and equipment [33]. In this situation, the grid has been removed from the inverter, which then only supplies local loads. This can be troublesome for many high-power transformerless systems, since a single-phase inverter with a neutral-to-line grid connection is a system grounded on the grid side.

In general, PV cells can be connected to the grid (grid-connection application), or they can be used as isolated power supplies. These two different applications of PV systems are shown in Fig. 10.

Several classifications of converter topologies can be done with respect to the number of power processing stages, location of power-decoupling capacitors, use of transformers, and types of grid interface. However, before discussing PV converter topologies, three designs of inverter families are defined: central inverters, module-oriented or module-integrated inverters, and string inverters [34], [35]. The central converters connect in parallel and/or in series on the dc side. One converter is used for the entire PV plant (often divided into several units organized in master–slave mode). The nominal power of this topology is up to several megawatts. The module-oriented converters with several modules usually connect in series on the dc side and in parallel on the ac side. The nominal power ratings of such PV power plants are up to several megawatts. In addition, in the module-integrated converter topology, one converter per PV module and a parallel connection on the ac side are used. In this topology, a central measure for main supervision is necessary.



(a) (b)

Fig. 11. (a) One-phase multistring converter. (b) Three-phase multistring converter.

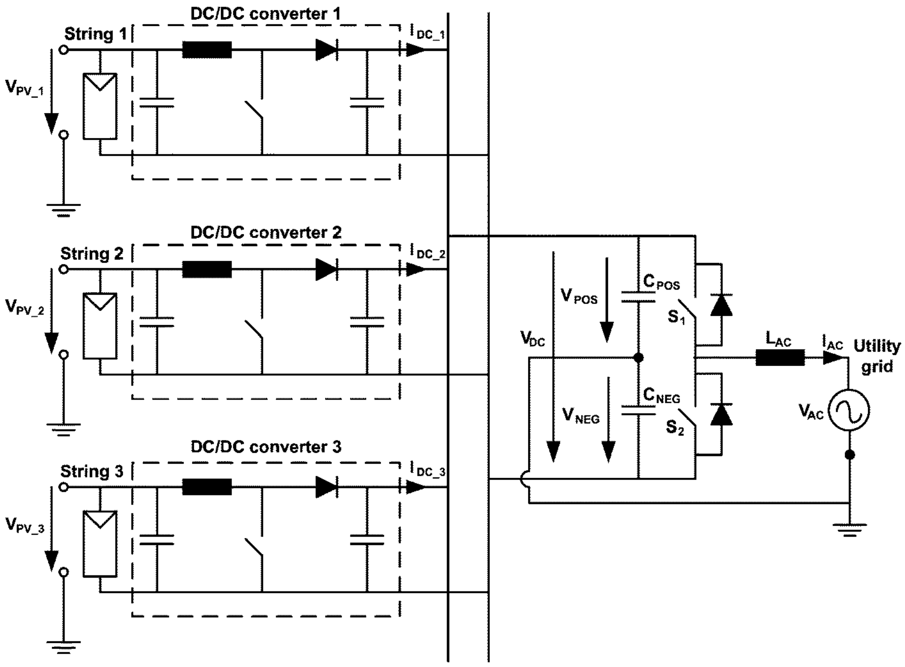


Fig. 12. Detail of a multistring converter with a single-phase inverter stage.

Although this topology optimizes the energy yield, it has a lower efficiency than the string inverter. This concept can be implemented for PV plants of about 50–100 W.

In Fig. 11, a one-phase multistring converter [Fig. 11(a)] and a three-phase multistring converter [Fig. 11(b)] are shown. A detail of a multistring converter with a single-phase inverter stage is illustrated in Fig. 12.

The multistring topology permits the integration of PV strings of different technologies and orientations (north, south, east, and west).

C. PV Topologies

Conventionally, a classification of PV topologies is divided into two major categories: PV inverters with dc/dc converter (with or without isolation) and PV inverters without dc/dc converter (with or without isolation) [34], [36].

The isolation used in both categories is acquired using a transformer that can be placed on either the grid or low-frequency (LF) side or on the HF side. The line-frequency transformer is an important component in the system due to its size, weight, and price. The HF transformer is more compact, but special attention must be paid to reduce losses [34], [37]. The use of a transformer leads to the necessary isolation (requirement in U.S.), and modern inverters tend to use an HF transformer. However, PV inverters with a dc/dc converter without isolation are usually implemented in some countries where grid-isolation is not mandatory.

Basic designs focused on solutions for HF dc/dc converter topologies with isolation such as full-bridge or single-inductor push–pull permit to reduce the transformer ratio providing a higher efficiency together with a smoother input current. However, a transformer with tap point is required. In addition, a double-inductor push–pull is implemented in other kind of applications (equivalent with two interleaved boost converters leading to a lower ripple in the input current), but extra inductor is needed [38]. A full-bridge converter is usually used at power levels above 750 W due to its good transformer utilization [34].

Another possible classification of PV inverter topologies can be based on the number of cascade power processing stages. The single-stage inverter must handle all tasks such as maximum-power-point-tracking (MPPT) control, grid-current control, and voltage amplification. This configuration, which is useful for a centralized inverter, has some drawbacks because it must be designed to achieve a peak power of twice the nominal power. Another possibility is to use a dual-stage inverter. In this case, the dc/dc converter performs the MPPT (and perhaps voltage amplification), and the dc/ac inverter is dedicated to control the grid current by means of pulsewidth modulation (PWM), space vector modulation (SVM), or bang–bang operation. Finally, multistage inverters can be used, as mentioned above. In this case, the task for each dc/dc converter is MPPT and, normally, the increase of the dc voltage. The dc/dc converters are connected to the dc link of a common dc/ac inverter, which takes care for the grid-current control. This is beneficial since a better control of each PV module/string is achieved, and that common dc/ac inverter may be based on a standard variable-speed-drive (VSD) technology.

There is no any standard PV inverter topology. Several useful proposed topologies have been presented, and some good studies regarding current PV inverters have been done [39], [40]. The current control scheme is mainly used in PV inverter applications [41]. In these converters, the current into the stage is modulated/controlled to follow a rectified sinusoidal waveform, and the task for the circuit is simply to recreate the sine wave and inject it into the grid. The circuits apply zero-voltage switching (ZVS) and zero-current switching (ZCS). Thus, only conduction losses of the semiconductors remain. If the converter has several stages, power decoupling must be achieved with a capacitor in parallel with the PV module(s). The current control scheme is employed more frequently because a high-power factor can be obtained with simple control circuits, and transient current suppression is possible when disturbances such as voltage changes occur in the utility power system. In the current control scheme, operation as an isolated power source is difficult, but there are no problems with grid interconnection operation.

PV automatic-control (AC) module inverters used to be dual-stage inverters with an embedded HF transformer. Classical solutions can be applied to develop these converters: flyback converters (single or two transistors), flyback with a buck–boost converter, resonant converters, etc. For string or multistring systems, the inverters used to be single or dual-stage inverters with an embedded HF transformer. However, new solutions try to eliminate the transformer using multilevel topologies.

A very common ac/dc topology is the half-bridge two-level VSI, which can create two different voltage levels and requires double dc-link voltage and double switching frequency in order to obtain the same performance as the full bridge. In this inverter, the switching frequency must be double the previous one in order to obtain the same size of the grid inductor. A variant of this topology is the standard full-bridge three-level VSI, which can create a sinusoidal grid current by applying the positive/negative dc-link or zero voltage, to the grid plus grid inductor [42]. This inverter can create three different voltages across the grid and inductor, the switching frequency of each transistor is reduced, and good power quality is ensured. The voltage across the grid and inductor is usually pulsewidth modulated but hysteresis (bang-bang) current control can also be applied.

Other multilevel topologies can be taken into account and in [43] cascade multilevel inverters are studied. Seven basic three-level cells can be used to achieve fifteen levels in the output signals without using an output transformer. This is beneficial for the power system and results in an improvement in the THD performance of the output signals. However, other problems such as commutation and conduction losses appear [34].

D. Future Trends

The increasing interest and steadily growing number of investors in solar energy stimulated research that resulted in the development of very efficient PV cells, leading to universal implementations in isolated locations [44]. Due to the improvement of roofing PV systems, residential neighborhoods are becoming a target of solar panels, and some current projects involve installation and setup of PV modules in high building structures [45].

PV systems without transformers would be the most suitable option in order to minimize the cost of the total system. On the other hand, the cost of the grid-connected inverter is becoming more visible in the total system price. A cost reduction per inverter watt is, therefore, important to make PV-generated power more attractive. Therefore, it seems that centralized converters would be a good option for PV systems. However,

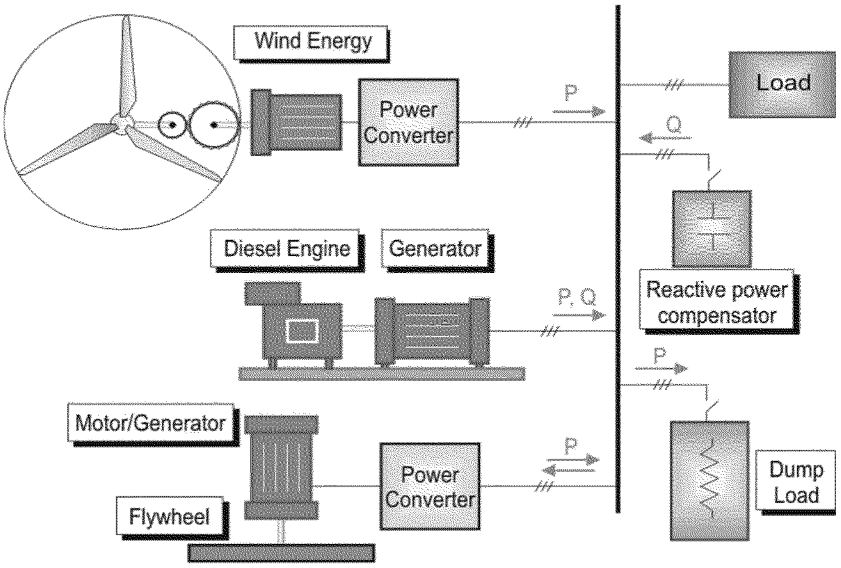


Fig. 13. Typical compensation system for renewable energy applications based on flywheel energy storage.

problems associated with the centralized control appear, and it can be difficult to use this type of systems.

An increasing interest is being focused on ac modules that implement MPPT for PV modules improving the total system efficiency. The future of this type of topologies is to develop “plug and play systems” that are easy to install for nonexpert users. This means that new ac modules may see the light in the future, and they would be the future trend in this type of technology. The inverters must guarantee that the PV module is operated at the maximum power point (MPP) owing to use MPPT control increasing the PV systems efficiency. The operation around the MPP without too much fluctuation will reduce the ripple at the terminals of the PV module.

Therefore, the control topics such as improvements of MPPT control, THD improvements, and reduction of current or voltage ripples will be the focus of researchers in the years to come [46]. These topics have been deeply studied during the last years, but some improvements still can be done using new topologies such as multilevel converters. In particular, multilevel cascade converters seem to be a good solution to increase the voltage in the converter in order to eliminate the HF transformer. A possible drawback of this topology is control complexity and increased number of solid-state devices (transistors and diodes). It should be noticed that the increase of commutation and conduction losses has to be taken into account while selecting PWM or SVM algorithms.

Finally, it is important to remember that standards, regarding the connection of PV systems to the grid, are actually becoming more and more strict. Therefore, the future PV technology will have to fulfil them, minimizing simultaneously the cost of the system as much as possible. In addition, the incorporation of new technologies, packaging techniques, control schemes, and an extensive testing regimen must be developed. Testing is not only the part of each phase of development but also the part of validation of the final product [44].

IV. STORAGE SYSTEMS

A. Flywheels

In order to improve the quality of the generated power, as well as to support critical loads during mains’ power interruption, several energy-storage technologies have been investigated, developed, proved, and implemented in renewable energy systems. However, flywheels are very commonly used due to the simplicity of storing kinetic energy in a spinning mass. For approximately 20 years, it has been a primary technology used to limit power interruptions in motor/generator sets where steel wheels increase the rotating inertia providing short power interruptions protection and smoothing of delivered power. One of the first commercial uses of flywheels in conjunction with active filtering to improve frequency distortion on a high-voltage power-system line is described in [47].

There are two broad classes of flywheel-energy-storage technologies. One is a technology based on low-speed flywheels (up to 6000 r/min) with steel rotors and conventional bearings. The other one involves modern high-speed flywheel systems (up to 60000 r/min) that are just becoming commercial and make use of advanced composite wheels that have much higher energy and power density than steel wheels. This technology requires ultralow friction bearing assemblies, such as magnetic bearings, and stimulates a research trend [48].

Most applications of flywheels in the area of renewable energy delivery are based on a typical configuration where an electrical machine (i.e., high-speed synchronous machine or induction machine) drives a flywheel, and its electrical part is connected to the grid via a back-to-back converter, as shown in Fig. 13. Such configuration requires an adequate control strategy to improve power smoothing [49]–[52]. The basic operation could be summarized as follows. When there is excess in the generated power with respect to the demanded power, the difference is stored in the flywheel that is driven by the electrical machine operating as a motor. On the other hand, when a perturbation or a fluctuation in delivered power is detected in the loads, the electrical machine is driven by the flywheel and operates as a generator supplying needed extra energy. A typical control algorithm is a direct vector control with rotor-flux orientation and sensorless control using a model-reference-adaptive-system (MRAS) observer.

Experimental alternatives for wind farms include flywheel compensation systems connected to the dc link, which are the same as the systems used for power smoothing for a single or a group of wind turbines [53]. Usually, a control strategy is applied to regulate the dc voltage against the input power surges/sags or sudden changes in the load demand. A similar configuration can be applied to solar cells [54]. Another renewable energy resource where power oscillations need to be smoothed is wave energy. In [55], a D-static synchronous compensator (STATCOM) is proposed, as an alternative to flywheels, to accomplish the output power smoothing on a wave-energy converter where several operating conditions should be taken into account. Recent proposals on using flywheels to regulate the system frequency include the disposal of a matrix of several flywheels to compensate the difference between the network's load and the power generated [56].

Recently, there has been research where integrated flywheel systems can be encountered. Those systems use the same steel rotor of the electrical machine as energy-storage element [57]. Two of the main advantages of a system like that are its high-power density and its similarity with a standard electrical machine. It seems that a new trend for energy storage in renewable energy systems is to combine several storing technologies (as what occurs in uninterruptible power system (UPS) application), where a storage system integrates compressed-air system, thermal storage unit, and flywheel energy storage [58].

B. Hydrogen

This section aims to analyze new trends in hydrogen-storage systems for high-quality back-up power. The hydrogen-fuel economy has been rapidly increasing in industrial application due to the advantages of the hydrogen of being storable, transportable, highly versatile, efficient, and clean energy carrier to supplement or replace many of the current fuel options. It can be used in fuel cells to produce electricity in a versatile way, for example, in portable applications, stationary use of energy, transportation, or high-power generation. The use of fuel cells in such applications is justified since they are a very important alternative power source due to their well-known specific characteristics such as very low toxic emissions, low noise and vibrations, modular design, high efficiency (especially with partial load), easy installation, compatibility with a lot of types of fuels, and low maintenance cost.

The increase of the penetration of renewable energies worldwide makes the storage issue critical both in stand-alone [59] and grid-connected application. An example of the hydrogen-storage application to improve the grid power quality through smoothing large and quick fluctuations of wind energy is reported in [60].

Hydrogen could be stored as compressed or liquefied gas [61] or by using metal hydrides or carbon nanotubes [62]. For a particular application, the choice of a storage technology implies a tradeoff between the characteristics of available technologies in terms of technical, economical, or environmental performance [63]. Applications must also include a discussion of the life-cycle efficiency and cost of the proposed storage system. This analysis should consider the total life of the proposed hydrogen-storage system including raw-material requirements, manufacturing and fabrication processes, integration of the system into the vehicle or off-board configuration, useful service life, and removal and disposal processes including recycling. Recently, research and development are focused on new materials or technologies for hydrogen storage: metal hydrides (reduce the volumetric and pressure requirements for storage, but they are more complex than other solutions), chemical hydrides, carbon-based hydrogen-storage materials, compressed- and liquid-hydrogen-tank technologies, off-board hydrogen-storage systems (a typical refueling station will be delivering 200–1500 kg/day of hydrogen), and new materials and approaches for storing hydrogen on board a vehicle. Applications to identify and investigate advanced concepts for material storage that have the potential to achieve 2010 targets of 2 kWh/kg and 1.5 kWh/L.

C. Compressed-Air Energy Storage (CAES)

Energy storage in compressed air is made using a compressor that stores it in an air reservoir (i.e., an aquifer like the ones used for natural-gas storage, natural caverns, or mechanically formed caverns, etc.). When a grid is operating off peak, the compressor stores air in the air reservoir. During discharge at peak loads, the compressed air is released to a combustor where it is mixed with oil or gas driving a gas turbine. Such systems are available for 100–300 MW and burn about one-third of the premium fuel of a conventional simple cycle combustion turbine.

An alternative to CAES is the use of compressed air in vessels (called CAS), which operates exactly in the same way as CAES except that the air is stored in pressure vessels rather than underground reservoirs. Such difference makes possible variations consisting of the use of pneumatic motor acting as compressors or driving a dc motor/generator according to the operation required by the system, i.e., storing energy when there is no extra demand of energy or delivering extra power at peak loads.

Recent research is devoted to the maximum-efficiency point-tracking control [64] or integrated technologies for power-supply applications [58].

D. Supercapacitors

Supercapacitors, which are also known as ultracapacitors or electric double layer capacitors (EDLC), are built up with modules of single cells connected in series and packed with adjacent modules connected in parallel. Single cells are available with capacitance values from 350 to 2700 F and operate in the range of 2 V. The module voltage is usually in the range from 200 to 400 V. They have a long life cycle and are suitable for short discharge applications and are less than 100 kW. New trends focused on using ultracapacitors to cover temporary high peak-power demands [65], integration with other energy-storage technologies, and development of high-voltage applications.

E. Superconducting Magnetic Energy Storage (SMES)

In an SMES, a coil of superconducting wire stores electrical energy in a magnetic field without resistive losses. Also, there is no need for conversion between chemical or mechanical forms of energy.

Recent systems are based on both general configurations of the coil: solenoidal or toroidal. The second topology has a minimal external magnetic field but the cost of superconductor and coil components is higher than the first topology. Such devices require cryogenic refrigerators (to operate in liquid helium at -269 °C) besides the solid-state power electronics.

The system operates by injecting a dc current into the superconducting coil, which stores the energy in magnetic field. When a load must be fed, the current is generated using the energy stored in the magnetic field. One of the major advantages of SMES is the ability to release large quantities of power during a fraction of a cycle. Typical applications of SMES are corrections of voltage sags and dips at industrial facilities (1-MW units) and stabilization of ring networks (2-MW units).

New trends in SMES are related to the use of low-temperature superconductors (liquid-nitrogen temperature), the use of secondary batteries, and the integration of STATCOM [66] and several topologies of ac–dc–ac converters with SMES [67].

F. Battery Storage

The use of batteries as a system to interchange energy with the grid is well known. There are several types of batteries used in renewable energy systems: lead acid, lithium, and nickel.

Batteries provide a rapid response for either charge or discharge, although the discharge rate is limited by the chemical reactions and the type of battery. They act as a constant voltage source in the power systems. New trends in the use of batteries for renewable energy systems focused on the integration with several energy sources (wind energy, PV systems, etc.) and also on the integration with other energy-storage systems complementing them. Also, there are attempts to optimize battery cells in order to reduce maintenance and to increment its lifetime [68].

G. Pumped-Hydroelectric Storage (PHS)

As batteries, PHS is a mature technology where a swamp of water stored at a certain high elevation is used to generate electric energy by hydroturbines, whenever there is an additional power demand in the grid. When no extra generation is needed, the water is pumped back up to recharge the upper reservoir. One limitation of PHS is that they require significant land areas with suitable topography. There are units with sizes from 30 to 350 MW, with efficiencies around 75%.

New trends in PHS are focused on the integration with variable-speed drives (cycloconverters driven doubly fed induction machine) [69] and the use of underground PHS (UPHS), where the lower reservoir is excavated from subterranean rock. Such a system is more flexible and more efficient but requires a higher capital cost.

V. CONCLUSION

The new power-electronic technology plays a very important role in the integration of renewable energy sources into the grid. It should be possible to develop the power-electronic interface for the highest projected turbine rating, to optimize the energy conversion and transmission and control reactive power, to minimize harmonic distortion, to achieve at a low cost a high efficiency over a wide power range, and to have a high reliability and tolerance to the failure of a subsystem component.

In this paper, the common and future trends for renewable energy systems have been described. As a current energy source, wind energy is the most advanced technology due to its installed power and the recent improvements of the power electronics and control. In addition, the applicable regulations favor the increasing number of wind farms due to the attractive economical reliability. On the other hand, the trend of the PV energy leads to consider that it will be an interesting alternative in the near future when the current problems and disadvantages of this technology (high cost and low efficiency) are solved. Finally, for the energy-storage systems (flywheels, hydrogen, compressed air, supercapacitors, superconducting magnetic, and pumped hydroelectric), the future presents several fronts, and actually, they are in the same development level. These systems are nowadays being studied, and only research projects have been developed focusing on the achievement of mature technologies.

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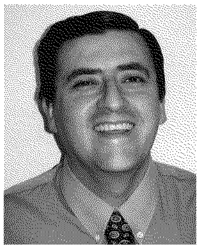

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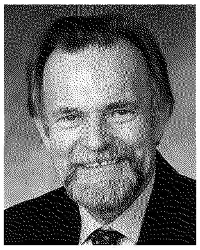

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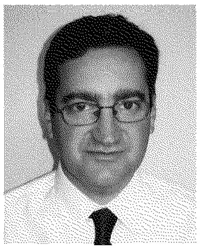

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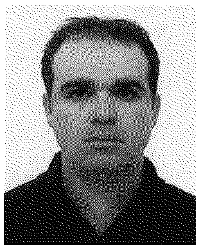

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ATTACHMENT 5

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Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies

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Abstract

In this work, we evaluate technologies that will enable solar photovoltaics (PV) to overcome the limits of traditional electric power systems. We performed simulations of a large utility system using hourly solar insolation and load data and attempted to provide up to 50% of this system's energy from PV. We considered several methods to avoid the limits of unusable PV that result at high penetration due to the use of inflexible baseload generators. The enabling technologies considered in this work are increased system flexibility, load shifting via demand responsive appliances, and energy storage.

Keywords: Solar; Photovoltaics; Energy storage

1. Introduction

Over the next few decades, it is possible that the demand for carbon-free electric power generation will dramatically increase the use of intermittent renewable sources such as solar photovoltaics (PV). In our previous analysis (Denholm and Margolis, 2007), we examined the inherent limits of traditional electric power systems to accept very large amounts of PV energy. A large fraction of PV electricity generation occurs when normal electricity demand is relatively low, and the existence of large inflexible thermal steam plants results in unusable PV, resulting in increased costs. At some point when PV is supplying in the range of 10–20% of a system's energy, the cost penalties and ''diminishing return'' of increasing PV generation will likely limit the economic use of this generation technology.

In this work, we examine several options to increase the penetration of solar PV beyond 20% of a system's energy. We begin by reviewing the cost impacts of PV at high penetration in ''conventional'' electric power systems. We then discuss qualitatively, and analyze quantitatively three approaches that could increase the usefulness of PV generation. The first is increasing the system's flexibility by increasing the ramping capability and decreasing the minimum load on conventional generators. The second is increasing the effective coincidence of PV supply and electricity demand by the use of load shifting. And the third is energy storage which provides the ''ultimate'' solution by allowing excess PV generation to be stored and delivered at a later time. This analysis includes results from simulations of each of these alternatives in an attempt to quantify approaches to increase PV penetration in the electric power system.

1.1. Surplus PV generation and resulting costs

In our previous work, we demonstrated the impacts of limited coincidence between PV generation and normal demand (Denholm and Margolis, 2007). While there is considerable coincidence between solar insolation and normal demand in the summer, there is less coincidence during other months. We simulated the output of a large, spatially diverse PV generation system in the Electric Reliability Council of Texas (ERCOT) electric power

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system using recorded insolation data at nine sites throughout the state, at seven different orientations, using the PVflex tool. Both hourly insolation data and hourly load is from the year 2000. The simulated output was combined with recorded load to determine how much PV would be "usable" during each hour of the year at different levels of PV penetration.

The amount of usable PV is largely determined by the flexibility of the existing electric power system to vary load. In our previous work, we defined system flexibility as the fraction below annual peak to which a conventional generation fleet may reduce output. This minimum load is based on a variety of technical and operational constraints, including the long ramp times of nuclear plants, the stability limits on coal-fired steam plants, the required amount of plants operating as "spinning reserve", etc. We suggest that a flexibility factor of 60–70% represents a typical flexibility factor for much of the US, based on historical electricity market data. When the load drops to below 30–40% of annual peak, wholesale electricity prices often drop below the actual variable costs of producing electricity (PJM, 2005); this implies that generators are willing to sell electricity at a loss in order to keep plants running. The flexibility factor of electric power systems will vary by region and by country. Systems dominated by nuclear power (such as France) will likely have less flexibility, while systems relying largely on hydroelectric generation (such as Norway) will probably have greater flexibility.

This minimum load constraint establishes in part the amount of PV-generated electricity that would have to be "spilled" at high penetration. As the amount of surplus PV generation increases, and as less and less PV generation is actually usable, the price of the actual PV generation that is usable increases. The relative energy cost is calculated according to:

$$\text{Relative PV energy cost} = \frac{1}{1 - \text{net PV energy spill rate}}, \qquad (1)$$

where the net spill rate is any unusable PV generation. The net spill rate can be evaluated at the margin (the fraction of generation from an incremental amount of PV that is unusable) or on the average (the fraction of generation from all PV that is unusable). When no PV is spilled, the relative energy cost is equal to 1, and as the spill rate approaches 100%, the relative cost approaches infinity. Fig. 1 shows the relationship between the fraction of the simulated system's energy produced by PV and the relative average and marginal costs for a flexibility factor of 60% and 70%. The cost calculation was performed by the PVflex tool.

The PVflex tool considers only the cost increases associated with spilled PV generation. While there are other cost considerations, such as the increased ancillary services associated with rapidly fluctuating generation, these costs are more difficult to model. In addition, the ability to integrate intermittent sources is improving, and it is unclear what limits short-term fluctuations in output will impose on future electric power systems (Parsons et al., 2006). The fundamental mismatch of PV generation and normal demand does, however, present an upper limit to the penetration of this renewable source.

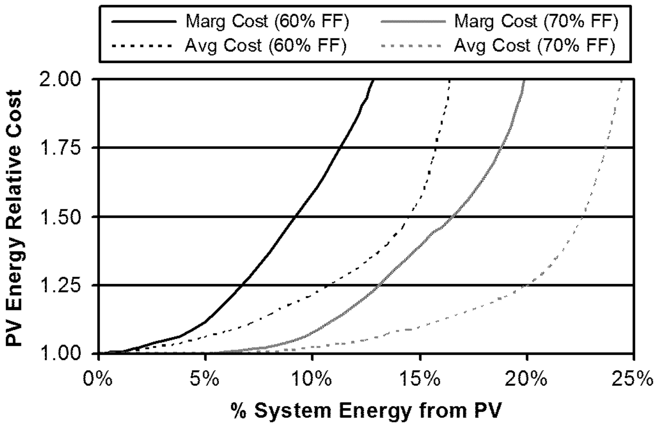

Fig. 1. Relative cost of PV electricity as a function of PV penetration for a flexibility factor (FF) of 60% and 70% (simulations are for ERCOT using 2000 load and insolation data).

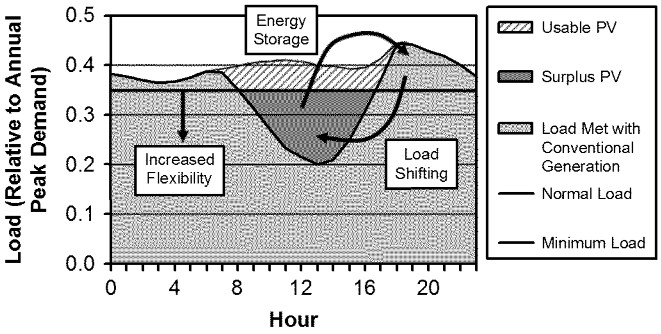

Fig. 2. Options for using surplus solar PV generation.

1.2. Options for surplus PV generation

The contribution of PV in the electric power system is ultimately limited by electricity demand that is not coincident with normal solar PV production, resulting unusable PV generation. To increase the usefulness of solar PV generation without incurring excessive cost penalties, the electric power system will need to change to absorb excess PV production.

Fig. 2 illustrates the "problem" of surplus PV generation and the three general approaches to utilizing surplus energy considered in this analysis. In this figure, the PV generation is subtracted from the normal load, with any generation that reduces the load to less than the minimum load considered surplus, and rejected from the system. In this example, enough PV has been installed to provide approximately 8% of the system's load on an annual basis, and the assumed minimum load (established by the flexibility of baseload units) is set to 35% of the annual peak demand, corresponding to a 65% flexibility factor. The dark area in this curve represents PV generation that would be unusable (surplus) due to the constraints on baseload power plants. It should be emphasized that this level of penetration represents a huge growth in PV capacity—to the point where PV represents about one-third of the system's generation capacity (Denholm and Margolis, 2007). While this level of penetration may take decades, it is useful to consider technical means to increase the economic penetration of solar PV.

The three general methods to increase the usefulness of this otherwise surplus PV generation considered here are:[2]

(1) Increased flexibility: lowering the system minimum allows more of the normal load to be met by PV.
(2) Load shifting: shifting normal load to times of greater PV output.
(3) Energy storage: storing solar generated electricity and releasing this stored energy at times of reduced or zero solar output.

In the following sections, we discuss each of the options in additional detail.

2. Increasing PV penetration via improved system flexibility

One important method of increasing the economic penetration of intermittent renewables such as solar PV is to increase the overall flexibility of the electric power system. Our previous work demonstrated how the limited flexibility of conventional electric power systems potentially restricts the penetration of intermittent renewables. This is illustrated in greater detail in Fig. 3, a load duration curve (LDC) for ERCOT for the year 2000. On the curve we have placed a minimum loading point set at 35% (equal to a flexibility factor of 65%). In conventional energy systems, all of the energy below this point (equal to about 62% of the total annual energy demand) would be met with inflexible baseload plants, limiting PV or other variable sources to the upper part of the LDC (which provides about 38% of the total annual demand).

By varying the minimum loading point in the load duration curve, we can examine the relationship between flexibility factor and annual energy that may be met by "variable" sources of power. This relationship is illustrated in Fig. 4. If we assume a "typical" flexibility factor of 60–70%, the inflexible baseload power plants provide from 54% to 71% of the total energy, leaving only 29–46% of the available load to the "variable" sources of electric power. As a result, for a traditional electric power system, even if PV could provide all of the energy in the variable part of the demand (through the use of storage for example), it would be unable to provide half of a system's energy with "normal" flexibility factors.

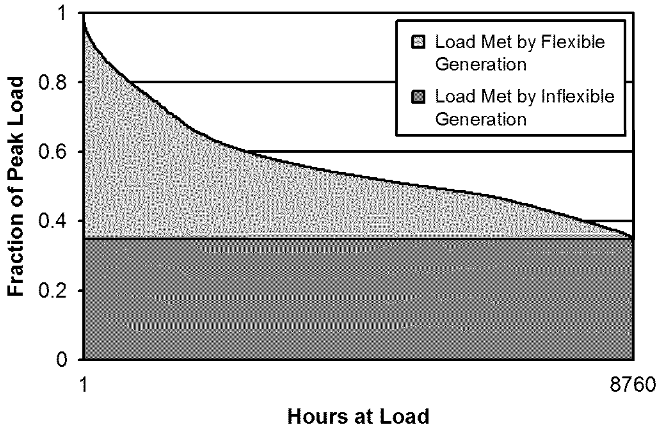

Fig. 3. Load duration curve for the ERCOT system in 2000.

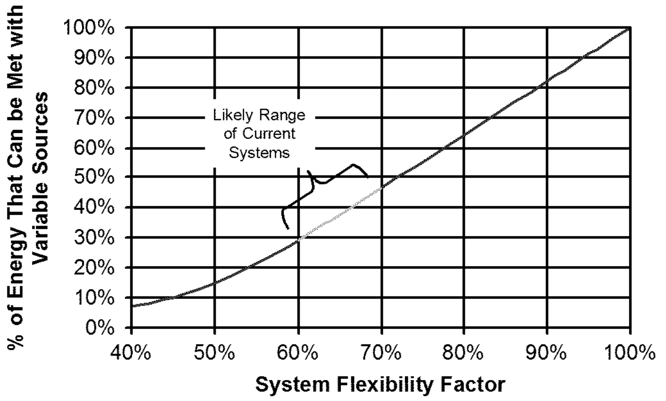

Fig. 4. Relationship between flexibility factor and energy produced by variable sources.

The implications of Fig. 4 are important for all intermittent sources of electricity generation in the future—any generation mix which derives a large fraction of its energy from intermittent sources will almost definitely need to be less reliant on plants which are unable to cycle.

While a flexibility factor of 60–70% may be representative of current systems, it may be possible to increase this value. The relationship between the fraction of the simulated system's energy produced by PV and the relative cost of PV is illustrated in Fig. 5, for a range of increasing system flexibility factors. We assume a 65% flexibility factor as our assumed "base" value for this graph and the remainder of this analysis.

Fig. 5 provides results for discrete flexibility factor values; since it is not possible to know exactly how "flexible" the electric power system will be in the future when PV electricity is economic enough to achieve these very high penetration levels, an alternative approach might be to ask how flexible the system would have to be to achieve specific goals of PV penetration and system cost. Fig. 6 indicates the required system flexibility as a function

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[2] There are additional possible uses for surplus PV generation that are not considered in this work. One of the most important may be introduction of new sources of dispatchable load, such as electrification of the transportation sector via pure electric or plug-in hybrid electric vehicles.

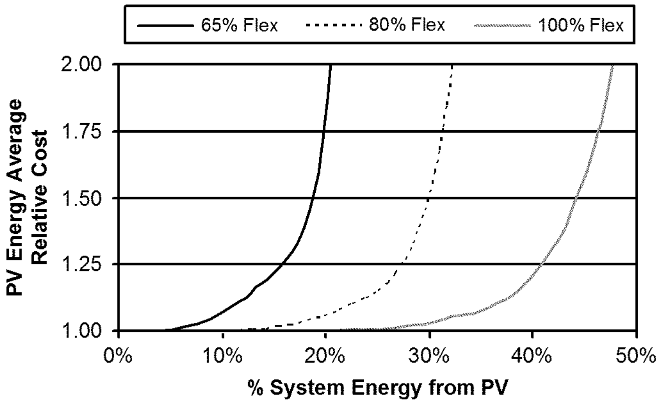

Fig. 5. Relative average cost of PV electricity as a function of PV penetration for a range of flexibility factors.

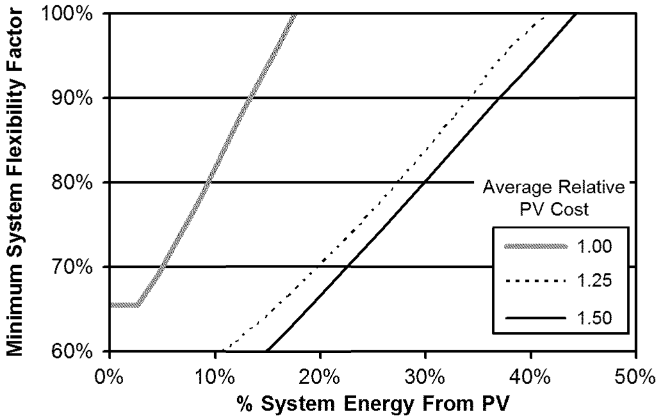

Fig. 6. System flexibility factors needed to achieve desired PV energy fraction and cost.

of PV penetration for a range of relative PV costs. The three curves shown in Fig. 6 indicate the maximum allowable average cost increase of 0%, 25%, and 50%. These values represent the "willingness to pay" for PV electricity at levels up to 1.5 times the "base" cost of PV. It should be emphasized that these are average costs, meaning that the cost of each and every kWh is 1, 1.25, or 1.5 times the base cost. At the margin, the costs are significantly higher for the 1.25 and 1.5 times cost scenarios. Each of the three "iso-cost" lines represents the minimum system flexibility required to meet the cost of PV at the desired PV energy penetration. For example, if no relative increase in PV costs were allowable, then the relative cost line of "1.00" indicates that a system flexibility of 80% would be required to achieve 10% energy by PV, and 100% to achieve 20% energy from PV.[3]

The small difference between the 1.25 and 1.5 relative cost curves cases indicates that this point is past the "knee" of the PV energy coincidence curve, so additional "willingness to pay" gains relatively small benefits in additional PV penetration. Clearly, increasing the flexibility factor of electric power systems is a necessary condition to increase the level of PV penetration beyond 10–20% of a system's energy; however, it is not a sufficient condition. Even at very high system flexibility, some use must be found for PV generation during periods of high PV output and low natural demand in order to avoid substantial cost penalties.

3. Increasing PV penetration with load shifting

One possible option for utilizing excess PV production is to increase the coincidence of PV output and electricity demand via load shifting. In this context, load shifting typically refers to a consumption neutral shift in the time of electricity use. To analyze the potential benefits of load shifting to increased PV deployment, we begin by identifying possible opportunities for load shifting, and then we provide results of simulations of load shifting using the PVflex tool.

3.1. Potential sources of load shifting

Load shifting from the day (on-peak) to the overnight (off-peak) time periods is encouraged by utilities by offering (or sometimes requiring) time-of-use rates to retail customers. Most existing time-of-use rate structures have fixed time periods for the on-peak and off-peak price periods, because daily demand patterns, and resulting generation cost patterns are generally understood based on historical load data (Cicchetti et al., 1977). The load-shifting requirements for PV enabling are considerably more challenging than those for traditional day/night shifting. A high PV-penetration scenario would essentially have two "off-peak" periods—the normal overnight period, and the much shorter "mid-day" off-peak period of excess PV production. (In this case "off-peak" refers to periods of low net demand, either because of naturally low loads, or the low net load resulting from large PV generation.) This mid-day off-peak period is considerably shorter than the overnight period, and is far less predictable. The amount of surplus PV (both energy and power) in this off-peak period also depends highly on weather conditions. As a result, the load-shifting scenario described here would almost certainly require instantaneous or "real-time" price signals that would indicate the availability of low-cost PV generation to consumers.

In addition to the short-term variation in PV output (hourly and daily), there is also a seasonal component to the variation in surplus PV output. We used the PVflex tool to identify when (on a seasonal basis) excess PV production occurs. In our simulated system, surplus PV generation is greatest on days with low mid-day demand, and relatively high solar PV output. In the ERCOT system, moderate

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[3] For no solar PV energy to be spilled, the flexibility factor must be greater than 1 minus the load during the hour that has the lowest demand with some solar generation. In the simulated ERCOT scenario, this hour occurs when the load is equal to 0.35 peak load, so the minimum flexibility factor for no energy to be spilled is equal to 65%; this produces the flat segment of the 1.0 iso-cost line.

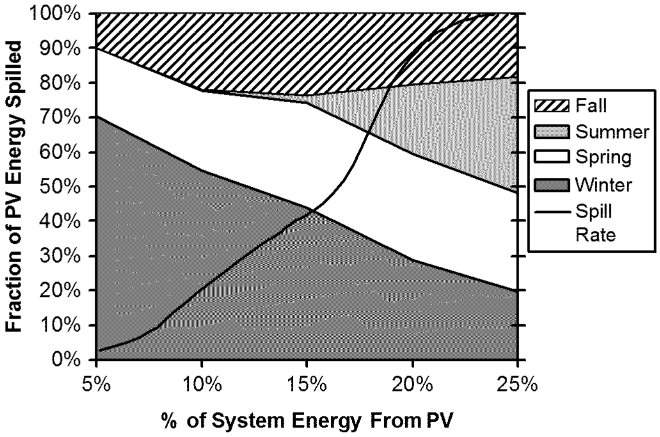

Fig. 7. PV energy spill rate and seasonal distribution of spilled energy.

temperatures (resulting in low heating and air-conditioning demand) and often clear conditions in the late winter and early spring lead to surplus production at moderate PV penetration. This is illustrated in Fig. 7, a plot of the marginal PV spill rate, along with the fraction of total spilled PV energy that occurs in each season, both as a function of PV penetration. The single line in Fig. 7 indicates the spill rate, starting at the point where PV is providing 5% of the system's energy, below which very little PV energy is spilled, up to the point where PV is providing 25%, where nearly all incremental PV energy is spilled. In addition to the marginal spill rate, the plot shows the distribution of which season the spilled energy occurs at various PV penetrations. The seasonal distribution graph is normalized, and the total fraction of PV energy spilled in each season can be calculated by multiplying the total spill rate by the seasonal fraction of spilled energy. The seasons were defined by the traditional calendar seasons, and the flexibility factor was set to 65%.

Fig. 7 indicates that load shifting would be most beneficial during the winter mid-day hours, particularly at low penetration. Until PV is providing about 10% of the system's energy, no spilled PV energy occurs during the summer. Beyond this point, the summer spill rate increases, until 25% PV energy penetration, where the distribution of spilled energy is simply the distribution of PV production, since the marginal spill rate is close to 100% at this point.

Load-shifting appliances might include ''smart'' appliances that can respond to real-time price signals and the unique characteristics of solar PV generation. One possible application is electric hot water heaters in commercial and residential buildings, which consume about 4% of US electricity (EIA, 2006). Another possible source of load shifting is water pumping, which uses about 3% of US electricity (EPRI, 2000). It is difficult to estimate the total potential of load shifting that can be applied to PV; much of the focus of load-shifting and demand–response studies is on its ability to reduce peak capacity requirements as opposed to time shifting of bulk energy demand (Neumann et al., 2006; FERC, 2006). While it is beyond the scope of this paper to identify and quantify all possible applications, we assume that the growing availability of real-time price signals and smart devices will increase load-shifting opportunities significantly (Levy, 2006).

3.2. Simulation of load shifting

We evaluated cases where up to 10% of each day's normal demand can be shifted to absorb excess PV generation. This 10% limit is somewhat arbitrary, however, it does reflect the fact that most loads are driven by fairly fixed schedules. These relatively fixed demand profiles are driven by the need for lighting, computer use, cooking, etc., or activities (including many industrial processes) that cannot be economically shifted to the narrow window of surplus PV output.

Above, in Section 2, the maximum PV energy penetration was a function of two variables: flexibility of conventional generators and the maximum PV spill rate (and resulting costs). Here a third variable is added: the amount of shiftable electric load. The PVflex model performs PV load shifting by subtracting a specified fraction of normal daily electricity demand, and adding it to demand met by PV, constrained by the amount of energy allowed to be shifted. All shifted load is considered consumption neutral, meaning there are no losses associated with time shifting load. In addition, the model also imposes a capacity constraint, since it assumed that most load-shifting appliances have an upper limit to the rate at which energy can be used. To establish a capacity constraint in our load-shifting assumptions, we used residential electric water heating as our ''base'' technology.[4] This assumption establishes a relationship that each 1% of load shifted (on an energy basis) may be absorbed by PV at a rate of up to 6% of the system's peak capacity.

Fig. 8 illustrates the effect of load shifting on relative PV cost for shiftable loads equivalent to 5% and 10% of each day's normal demand. In these simulations, the system flexibility factor was set at 65%. As before, the rising cost lines are driven by surplus PV generation, however, adding load shifting to the system enables higher levels of PV penetration at a given relative cost.

The relationship between increased PV penetration and shifted load can also be examined using iso-cost lines. Fig. 9 is identical to Fig. 6, except a 5% load shift has been introduced. While the iso-cost lines in Fig. 9 give a sense of the potential impact of load shifting, it is important to recognize that these curves do not include the capital cost

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[4] Total residential electric water heating energy consumption in Texas in 2001 was about 8 TW h, in 3 million households with electric water heating (EIA, 2006). Adjusting for the fraction of population within ERCOT (85%), this is about 2.4% of the total annual electricity demand. Assuming each home has one water heater with a rating of 3.5 kW, this corresponds to about 9 GW of combined demand, or about 15.4% of the annual peak demand. This relationship is not used to establish the amount of shiftable load—only the relationship between the quantity of shifted load (energy) and the capacity of shifted load (power).

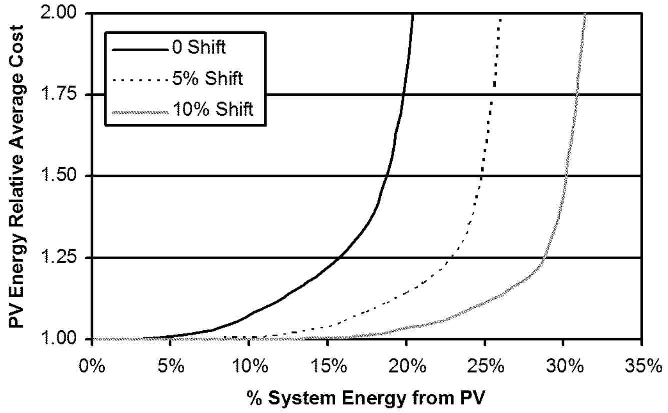

Fig. 8. Average cost of PV electricity as a function of energy penetration with three load-shift factors.

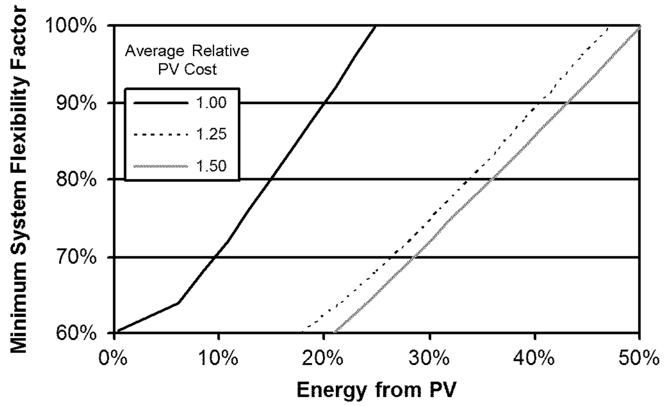

Fig. 9. System flexibility factors needed to achieve desired PV energy fraction and cost with 5% load shifting.

of load-shifting technologies, nor do they include subsidies or discounts necessary to incentivize load shifting.

There are several limits to the benefits of load shifting, including the seasonal variation in PV output, and also the strong concentration of mid-day solar output. As a result, shifted load in the winter season will be saturated by surplus PV generation before shifted load in the summer, limiting the overall annual benefits of load shifting. In addition, there may be times when the amount of shifted load is restricted by the maximum power capacity of the load-shifting appliance. Our assumption of electric water heating results in very high load-shifting capacity; while this is an almost ideal application for PV load shifting, other appliances, such as pumps, may have a more limited rate at which surplus PV can be consumed.

4. Increasing PV penetration with energy storage

The limits of fixed demand patterns may be overcome with the use of energy storage, which effectively shifts the supply of PV to any time schedule desired. While there are limits to how much demand might be shifted, virtually any amount of supply may be shifted with sufficient energy storage. Energy storage is similar to load shifting, although generally not consumption neutral due to the inherent inefficiencies in any energy-storage process. The distinction is somewhat blurred is some cases, such as thermal energy storage. Energy storage may make economic sense if the difference between on-peak and off-peak electricity exceeds the capital costs of the storage device and the costs associated with storage losses (Ter-Gazarian, 1994).

Energy storage represents perhaps the ''ultimate'' solution to the problem of intermittent generation. Energy storage increases the usefulness of PV in two ways. First it absorbs excess PV and allows PV energy to be used when it is not produced—in the evenings, on cloudy days, etc. Just as important, but perhaps less obvious, is the increased flexibility in utility system operation allowed by large-scale energy-storage deployment. As indicated in Section 1 of this work, a traditional electricity system dependent on baseload plants will have limited headroom for PV and other intermittent generators, and allow PV energy to be used only in the ''variable'' part of the daily load curve. The combination of PV and storage could effectively replace baseload generation, and thus increase the penetration of variable source generation in the system.

4.1. Energy-storage technologies

Several utility-scale energy-storage systems are currently deployed including pumped hydro storage and compressed air energy storage (CAES). Both technologies are generally large scale (tens to hundreds of MW) and have unique geological and geographic requirements (Denholm and Kulcinski, 2004). Batteries are more scalable in size and do not depend on availability of water or air storage. Batteries may also be located close to load, decreasing transmission and distribution losses. The round-trip efficiency of these technologies ranges from around 75% to 85% (Linden and Reddy, 2002).

The size of an energy-storage system has two components: energy (how much energy may be stored) and power (what is the rate of charge and discharge.) The relative size of the energy and power components may be independent of one another, depending on the storage technology. The relationship between energy and power in an energy-storage system may be expressed by the energy/power ratio, expressed by the amount of time a fully charged storage system can discharge at its maximum-rated capacity. Typical utility-scale energy-storage systems have energy/power ratios of 4–16 h. In addition, for some energy-storage systems, the maximum input (charging) and output (discharging) power ratings may be sized independently (Denholm and Kulcinski, 2004). This may be important for PV, as illustrated in the next section.

4.2. Simulation of PV systems with energy storage

The PVflex tool can simulate energy storage of any desired energy or power capacity.

In each hour, any excess PV generation ''charges'' the system constrained by its energy and power limits. Any time the storage system energy or power capacity is exceeded, the excess PV energy is considered spilled. Stored energy is then used during periods of low or zero PV output. The amount of energy discharge is constrained, however, by the specified discharge energy and power capacity, as well as the system's flexibility factor. Just as with PV, the storage system cannot discharge if the load is at or below the minimum loading level established by the flexibility factor.

During each hour of the year, PVflex accounts for three possible allocations of PV generated energy: energy used directly to meet normal load, energy stored, and energy spilled due to the limits of the load and storage system size. Of the PV energy stored, a certain fraction is lost due to inefficiencies. This leads to two general dispositions of PV energy: energy used either directly or via storage, or energy effectively spilled via surplus production or through storage inefficiencies.

Fig. 10 illustrates an example of the disposition of energy on an hourly basis over a 2-day period (February 19 and 20). These two days are in late winter, a period of relatively low mid-day demand, peaking at slightly more than half the annual peak demand. In this simulation, we used the following assumptions: the battery is sized to provide 3 h of average system demand, with an energy/power ratio of 12 h, and a round-trip efficiency of 75%. Also, the net PV system was sized to provide 20% of the system's energy, with 85% of all solar energy used either directly or via useful storage.

Several curves are shown in Fig. 10. The total solar generation is represented by the ''envelope'' of the directly usable solar, stored solar, and spilled solar. The direct usable solar is limited by the area between the normal load and the minimum load, in this case set to 35% of the annual peak, representing a flexibility factor of 65%. Any generation above the amount directly usable must be stored or spilled. In this particular case, the amount of energy stored is not limited by the energy capacity, but the power capacity. The power capacity of the battery is sized at about 15% of peak load, which is exceeded for a few hours in the mid-day by the strong PV output. The net load curve includes the load reduction from the directly usable solar in the middle of the day, where the net load drops to the minimum load. When PV output drops, the storage system discharges, and the net load drops to a value constrained by the energy capacity of the storage system. The particular dispatch algorithm illustrated in Fig. 10 is not implied to be the optimal—the storage systems would probably be dispatched on a longer term basis to optimize battery capacity and the use of conventional generation. However, the figure illustrates the general principle of the charge/discharge cycle that might result from large-scale deployment of PV and storage.

An ''optimal'' energy-storage system designed for PV might have a different power rating for the charging and discharging process. This is illustrated in Fig. 10, where a maximum charging rate equal to 15% of the annual peak load was unable to absorb all PV generation during the daily peak, but was discharged at a much lower rate. In this example, no specific energy-storage system was modeled. Instead, we chose a generic storage technology with a round-trip storage efficiency of 75%. While PVflex can accommodate different charging and discharge power capacities, they were set equal for this analysis.

The general relationship between usable PV, stored PV, and spilled PV energy as a function of PV penetration is provided in Fig. 11. In this case, the flexibility factor was set to 65%, and the energy-storage system was sized to 8 h of average hourly demand. The figure shows the marginal allocation of solar energy as a function of system energy from PV. At low penetration (below about 4% percent) all PV is used directly. From about 4% to 18% penetration, all of the surplus PV generation is stored and the only losses are due to the inefficiencies in the storage process. As

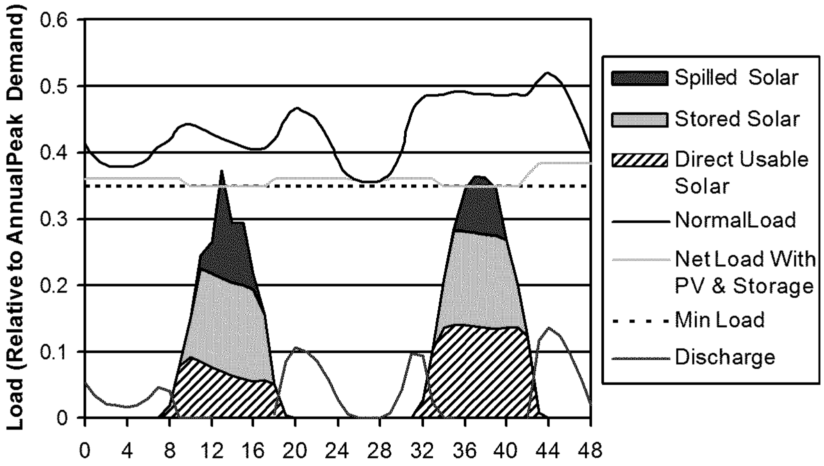

Fig. 10. Allocation of PV energy (usable, stored, and surplus) in a simulated system storage on 2 days in February.

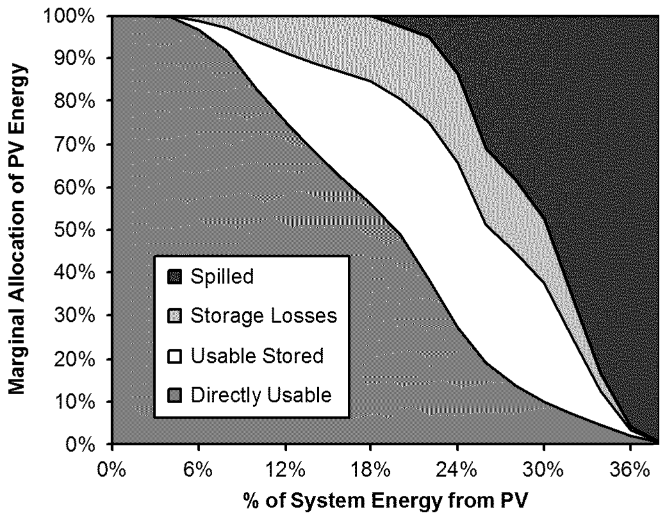

Fig. 11. Allocation of PV energy in a system with 8 h of storage.

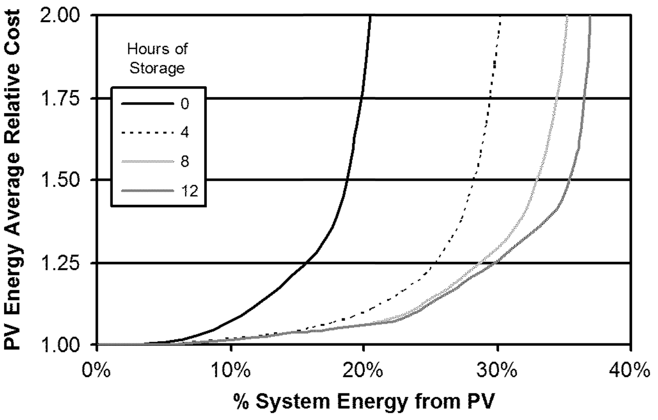

Fig. 12. Average cost of PV electricity as a function of energy penetration with three storage sizes.

penetration increases a greater fraction of PV generation needs to be stored and associated storage losses also increase. However, there is a limit to the amount of energy that can be absorbed by the storage system. In this example, when roughly 18% the system's energy is from PV, some PV begins to be spilled directly.

Since energy storage involves losses, the effective spill rate for PV generation is the sum of direct-spilled PV and storage losses. While difficult to see in the figure, the relationship between usable stored energy and storage losses in the PVflex model is a constant determined by the storage efficiency, in this case set at 75%.

Fig. 12 illustrates the effect of introducing energy storage on the average cost of PV generation. In this figure, three storage sizes are introduced equal to 4, 8, and 12 h of average demand, with the flexibility factor set to 65%. It is important to note that the costs in Fig. 12 are associated only with PV generation and do not consider capital or operation cost of the storage system.

The relatively small increase in benefits of the 12 h storage compared to the 8 h storage is an indication of the limits of system flexibility. As demonstrated previously in Fig. 4, the theoretical limit of variable sources in a system with a 65% flexibility factor is about 38%. In the case where 12 h of storage is available, PV is providing about 36% of the system's energy by the point it has an average cost of twice the base cost (representing a 50% net loss rate from energy spilled and storage inefficiencies). At this point PV is providing nearly all of the variable part of the system's demand, and to increase its contribution further, it must be able to replace baseload units.

As noted before, adding energy storage may allow PV to effectively replace baseload generation by adding reliable capacity, and increase the overall system flexibility. Choosing the size of an energy-storage system to be used with PV at high levels of penetration is ultimately an economic optimization problem involving system flexibility, storage energy and power capacity, and allowable PV spill rate. However, by fixing a few of these parameters, we can examine the storage size necessary to achieve high penetration rates at relatively low net spill rates.

Fig. 13 illustrates one possible scenario combining PV, storage, and variable system flexibility. In this case, the graph identifies all combinations that result in a net PV cost of generation equivalent to 1.25 times the base cost of PV generation. This figure is equivalent to a single iso-cost line (equal to 1.25) in Figs. 6 and 9. Note that an iso-cost line of 1 cannot be generated, since storage losses will always increase the net cost of PV generated electricity. Each color band represents a 10% range of PV contribution, from 10% to 20% in the lower left-hand corner, where there is a combination of low flexibility and little storage, to 60–70% of total system load with high flexibility and up to 12 h of storage.

In Fig. 13, we see that for a 25% increase in average PV cost, a combination of storage and increased flexibility could enable PV to achieve very high levels of penetration. For example, with 11 h of storage and an 80% flexibility factor PV could provide roughly 50% of the system's energy. An alternative to picking a fixed cost target is to pick a fixed energy target and evaluate the resulting costs with various storage sizes and system flexibilities. Fig. 14 illustrates this alternative approach, fixing the contribution of PV to 50% of the system's energy. In the lower left-hand corner are systems that have costs greater than twice the base cost, or in some cases, cannot provide 50% of the systems energy at any cost. In the upper right-hand corner are systems that provide 50% of the systems energy at a PV generation cost of up to 1.2 times the base cost.

As before, the costs illustrated in Fig. 14 do not provide an overall measure of the total PV-related system costs, since they do not include the capital costs of the storage technology, or storage system operation and maintenance. The cost curve is only one part of an optimization problem that will need to consider all factors, including the fact that an energy-storage system will likely be shared among a

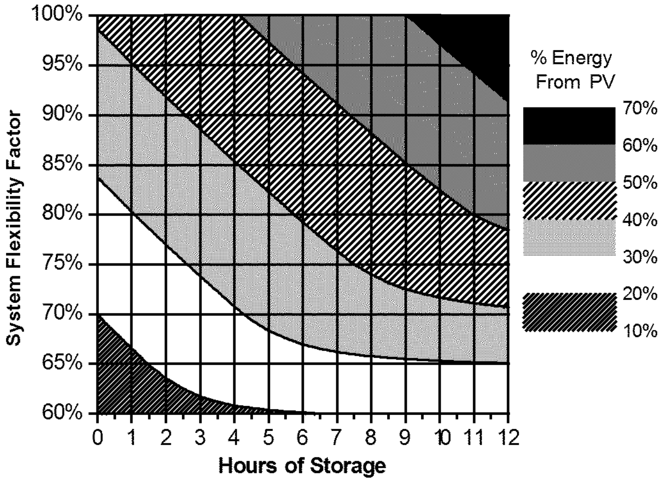

Fig. 13. System configurations that deliver PV energy at a net cost of 1.25 times the base cost of PV generation.

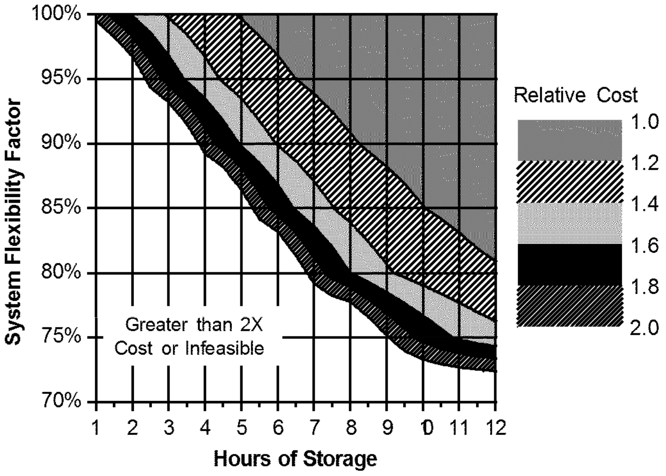

Fig. 14. Costs and system requirements associated with PV providing 50% of the system's energy requirements.

variety of generators including conventional and additional intermittent sources. A number of tools exist that can optimize a hybrid generation system including PV and storage (National Renewable Energy Laboratory, 2005). However, the scenarios described in this work will likely require dramatic improvements in the cost and performance of both PV technologies and energy storage. Therefore, performing an economic optimization would be mostly conjectural and of limited use in the present.

5. Conclusions

There are at least two fundamental limitations to integrating large quantities of solar PV into an electric power grid: the fundamental mismatch of PV supply and electricity demand, and the limitations of conventional baseload generators to respond to rapid changes in load. At high penetration, significant excess PV production in the simulated system (ERCOT) occurs in the winter, spring, and fall during early afternoons. Some use for this energy must be found to avoid spilling this energy and increasing the average cost of PV generation. Increasing system flexibility is a critical component to solving the integration problem. Decreasing dependence on inflexible generation units and allowing increased use of PV during periods of low electricity demand is an important component of significant PV contribution on an annual basis. Even after increasing system flexibility, however, some additional accommodation must be made for excess PV generation, particularly during the non-summer seasons.

A number of ''enabling technologies'' exist that could potentially utilize excess PV production. In this paper, we have focused on two options: load shifting and energy storage. Load shifting is a largely demand side measure that will require the development of appropriate real-time price signals and ''smart'' appliances and devices that are able to shift load and respond to the variability in PV output. Energy storage is the ultimate solution with the potential to blur the line between intermittent and baseload generation technologies. We found that a storage system capable of storing substantially less than 1 day's worth of average demand could enable PV to provide on the order of 50% of a system's energy. This level of PV penetration would truly require a radical transformation of the electricity system—from a centrally controlled to a highly distributed and interactive system.

The discussion in this paper has focused on the role of PV in serving traditional electricity demand, albeit with a variety of enabling technologies. It would also be interesting to examine the potential role of PV in displacing energy applications currently met with fossil fuels. One possibility is the use of otherwise surplus or low-value PV to supply mid-day recharging for plug-in hybrid electric vehicles. This application would enable PV and other renewable energy technologies to replace non-renewable fuels, while increasing the use of PV generation, and possibly reducing the need for other, potentially more expensive enabling technologies such as dedicated energy storage.

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ATTACHMENT 6

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Properties and uses of storage for enhancing the grid penetration of very large photovoltaic systems

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abstract

In this third paper, which studies the hourly generation data for the year 2006 from the Israel Electric Corporation, with a view to incorporating very large photovoltaic (PV) power plants, we address the question: What properties should storage have in order to enhance the grid penetration of large PV systems in an efficient and substantial manner? We first impose the constraint that no PV energy losses are permitted other than those due to storage inefficiency. This constraint leads to powerful linkages between the energy capacity and power capacity of storage, and PV system size, and their combined effect on grid penetration. Various strategies are then examined for enhancing grid penetration, based upon this newfound knowledge. Specific strategies examined include PV energy dumping and baseload rescheduling both on a seasonal basis and shorter time periods. We found, inter alia, that at high grid flexibilities (in the range $ff=0.8$–1), PV grid penetration levels could be possible in the range 60–90% of annual requirements. Moreover, with appropriately designed storage and accurate forecasting, a future grid could be operated at $ff=1$.

1. Introduction

This is the third of a series of papers in which hourly generation data from the Israel Electric Corporation (IEC), for year 2006, are examined with the purpose of studying how to maximize the efficient input of photovoltaic (PV) generated power into the grid. The problem is non-trivial because of the ramping requirements that intermittent energy sources, such as PV, impose on a grid that already has to meet the fluctuating demand requirements of its customers.

In our first paper (Solomon et al., 2010a) we restricted our discussion to the simulated hourly output of a fixed flat-panel PV system at a single location (Sede Boqer) in the Negev Desert of Israel. There we adopted a definition of grid flexibility, ff, introduced by Denholm and Margolis (2007a):

$$ff = 1 - \frac{t_{min}}{t_{max}} \qquad (1)$$

where t_{min} and t_{max} are the minimum and maximum hourly output of the grid system, respectively. We found that the IEC grid, as operated during year 2006, had an effective flexibility factor close to $ff=0.65$ but that there were indications from the data that the technical (as opposed to economically optimal) flexibility could have been higher. In that paper we defined an hourly solarizable load as the difference between the total load and the baseload during that hour. The actual hourly baseload was found to vary somewhat throughout the year but by convention (Denholm and Margolis, 2007a), we replaced this variable baseload by a constant value equal to peak load minus ff multiplied by the peak load. We calculated the largest PV system that, without storage, could have fed all of its 2006 energy generation into the grid without the need to dump any unusable portion during any hour of the year—a so-called "no-dump" (ND) system. It turned out that for $ff=0.65$, a ND system would have provided only 2.7% of the annual energy requirements of the IEC grid during that year. However, were the grid to have been operated at $ff=0.8$, the annual grid penetration of a ND system could have been as high as 9.8%. It was also found that some improvement in annual grid penetration can be obtained by relaxing, in a modest manner, the strict no-dump requirement. Specifically, at a grid flexibility $ff=0.80$, 18.7% grid penetration could have been achieved for a slightly over-sized PV system that was allowed to dump 5% of its annual energy generation.

In our second paper (Solomon et al., 2010b) we examined possible improvements that might have been brought about by the employment of various sun-tracking/technology types, specifically: 1-axis tracking flat panel PV, 2-axis tracking flat panel PV and 2-axis tracking concentrator photovoltaics (CPV). We also

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examined the effect of distributing PV systems throughout the Negev Desert. We found that sun-tracking improves the grid penetration to a certain extent but that PV plant distribution is far less important than choosing a best single site. In that paper, the best annual grid penetration we could find for ff¼0.80, without storage, was in the vicinity of 23%, provided one had been prepared to dump 5% of the energy generated by the PV system.

In many studies of the potential grid penetration of very large scale PV systems, such as that by Faiman et al. (2007), it is generally assumed that storage will be available to buffer the time differences between solar availability and load requirements. However, one of the findings in our first paper (Solomon et al., 2010a) was that, for significant PV penetration enhancement using storage, the grid system must be operated at relatively high flexibility (ff 4 0.64, in the IEC case). Otherwise there will be competition for use of storage between solar generation and grid surplus energy. On the other hand, little is known about the various factors that affect storage performance in enhancing PV penetration. For example, in the study by Denholm and Margolis (2007b), using their ERCOT data set, they showed how storage can significantly improve grid penetration especially when grid flexibility is high. However, their work did not address the manner in which the required properties of storage depend upon PV system size.

In the present paper, instead of placing a priori limits on the energy and power capabilities of the storage system, as was done in the study by Denholm and Margolis (2007b), we allow the interaction between the electricity grid and solar PV output to determine the required properties of storage. In order to achieve this end, we place all of the hourly surplus PV energy from a given sized PV system (greater than 1 ND) into a hypothetical storage facility of arbitrary size and evaluate the required power capacity and energy capacity of the latter. In this approach, we first limit energy losses to those due to storage inefficiency alone. This approach enables us to clarify how a storage system may improve the grid penetration of PV energy, and factors that limit the role of storage to perform this task. Upon establishing the nature of this interaction, we present the result of simulations which suggest strategies for increasing grid penetration in a significant manner compared to the levels achieved in our previous papers. These strategies include, as previously examined (Solomon et al., 2010a, b) allowing some dumping of PV energy, but also a novel suggestion of seasonal baseload rescheduling.

2. Methodology

We first examine how the storage requirement varies as successively greater amounts of PV energy are supplied to the grid. For this purpose we make the simplifying assumption that the only losses associated with storage are its round trip efficiency, which for specificity and following Denholm and Margolis (2007b), we set equal to Z¼75%. Examples of storage systems with efficiencies at this level include pumped hydro (Denholm and Kulcinski, 2004; Ibrahim et al., 2008; Schoenung et al., 1996; Ter-Gazarian, 1994) compressed air energy storage (Denholm and Kulcinski, 2004; Greenblatt et al., 2007) and various flow batteries (Ibrahim et al., 2008; Ter-Gazarian, 1994; Schaber et al., 2004; Skyllas-Kazacos and Menictas,1997). Moreover, technologies such as super-capacitors and flywheels are reported to be capable of even higher efficiencies (Ibrahim et al., 2008; Ter-Gazarian, 1994; Schaber et al., 2004; Schoenung et al., 1996).

We consider a storage system sufficiently large that it can accept all the surplus solar energy produced above the hourly solarizable part of the demand and supply it to the grid during hours when there is low or no solar power generation. As in our previous papers (Solomon et al., 2010a, b), the present analysis considers only technical, not economic constraints.

The computational technique is basically one of adding and subtracting on an hourly basis for an entire year. For this purpose a special computer algorithm was developed (Solomon et al., 2010a), a part of which, that is relevant to storage calculations, is summarized in Appendix I. The technique employed for the present discussion was to start with a ND PV system, and to systematically increase its size. For each size increase, we calculated the amount of storage, the so-called energy capacity (Denholm and Margolis, 2007b) that would be necessary to store the surplus PV energy that could not be fed directly to the grid during the hour in question.[1] In the graphs that are presented in the following section, it is convenient to employ ND as a unit that describes PV system size, for reasons that will be discussed later. However, it is important to realize that the magnitude of one ND unit of energy varies according to grid flexibility. In particular, for the flexibility values ff¼0.65, 0.70, 0.80 and 1, which are of chief interest to us in the following discussion, the respective ND sizes were shown to be (Solomon et al., 2010b): 827, 1,711, 3,046 and 5,389 MWp. For comparison, the total IEC generating capacity during 2006 was 10,487 MW (IEC, 2007). Moreover, these ND system sizes result from simulations of a fixed flat-panel PV system, located at Sede Boqer—the system type and location we shall employ, for the sake of specificity, throughout the present paper.

In addition to energy capacity, an important part of our discussion relates to the so-called power capacity[1] (Denholm and Margolis, 2007b). This is the maximum amount of energy that can be injected into or withdrawn from storage during a single hour. In principle, these are not necessarily the same but, for simplicity, we shall assume that they are the same. Moreover, initially, we shall formulate our discussion in terms of the maximum hourly charging rate requirement of storage. Later we will show how PV system size and demand profile create a relationship between the charging and discharging rate requirements of storage. It should be borne in mind, however, that in actual fact the true limitations on system performance caused by power capacity would need to be studied on a finer time scale than the hourly data presently at hand.

3. Results

3.1. Storage requirements

3.1.1. Energy capacity

In discussing storage, it is first useful to look at the magnitude of the entire problem. To this end, Fig. 1 shows the daily surplus energy, for grid flexibility ff¼0.70, generated by PV systems of size 3, 5 and 7 ND. By "daily surplus energy" we mean the daily sum of the amounts of hourly PV energy generated in excess of each hour's solarizable load (i.e. each hour's useable portion). Although, as we have previously indicated, the IEC grid is technically capable of being operated at a flexibility ff¼0.80, for the bulk of the present discussion we have preferred to employ ff¼0.70 as being representative of a modest increase above what was probably the economic optimum flexibility for year 2006.

From Fig. 1 we see that for all system sizes the bulk of surplus energy comes in springtime irrespective of system size. There is

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[1] Note: The use of round-trip efficiency, as explained in Appendix I, leads to a slight over-approximation of the energy capacity and power capacity of the required storage.

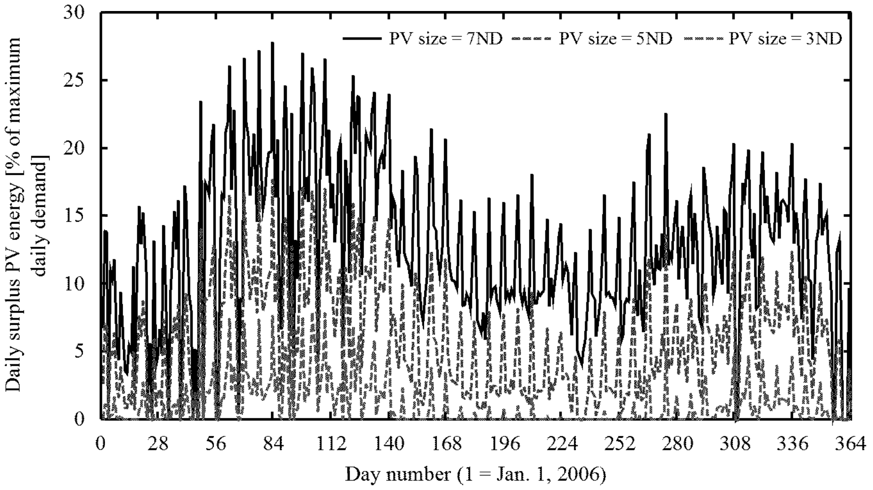

Fig. 1. Daily surplus PV energy, with ff¼0.70, normalized so that the maximum annual daily demand is unity.

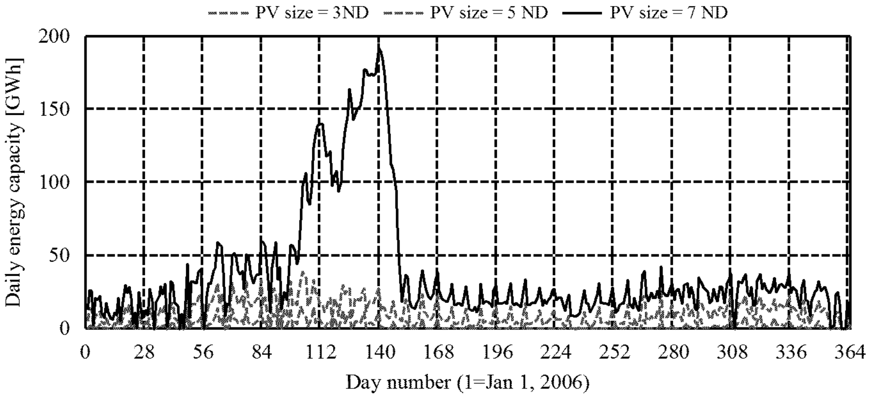

Fig. 2. Daily energy capacity requirement of storage, with ff¼0.7, for three PV system sizes.

little surplus energy throughout the summer—other than at weekends (signified by weekly spikes in the data). The surplus rises again in winter but it does not reach its spring maxima. These trends are understandable in terms of a combination of solar generation and electricity demand patterns (Solomon et al., 2010a). Storage must therefore be sized to accommodate these trends.

Accordingly, Fig. 2 shows the required daily storage energy capacity for PV systems of size, 3, 5 and 7 ND, for grid flexibility ff¼0.70. Fig. 2 implies that the annual required energy capacities for PV system sizes of 3, 5 and 7 ND are approximately 15, 40 and 200 GWh, respectively. Otherwise, energy would need to be dumped during the peak spring days. For comparison, the total annual energy generation of the IEC during 2006 was 50,372 GWh (IEC, 2007).

Fig. 2 confirms that in the case of a system sized at 3 ND, most of the storage requirement comes during springtime (March–May) and, to a lesser extent, during winter (particularly November). On the other hand, hardly any storage is required during the summer. The reason appears to be that the increasingly high springtime insolation levels come at a time of year before extensive air-conditioning is employed. Therefore, storage must be able to accommodate the spring season maximum daily over-generation of PV power (assuming, for the moment, that power capacity has no limiting effect). In summertime, the load requirement is so high that almost all energy generated by the PV system can be injected into the grid with very little need for storage. In wintertime, as previously indicated (Solomon et al., 2010a), there is a relatively poor match between daytime solar availability and the early evening peak loads when people return home from work. This is why storage is again needed. However, the required energy capacity of storage is not as high as in spring because the solar generation is lower.

As we increase the PV system size to 5 ND, Fig. 2 shows that nothing qualitatively different happens. The storage size obviously increases since the daily surplus energy increases as already seen in Fig. 1 but it is employed more evenly throughout the year.

Fig. 2 shows a spectacular difference when the system size is increased to 7 ND. In this situation, the peak requirement shifts forward to the pre-summer period terminating at approximately the end of May. What is happening here is that the PV system size has become so large that excessive surplus energy stored during daytime exceeds the solarizable load required during the following night. As a result storage is not empty when recharging starts the next day. As soon as the true summer load starts, the storage empties out in a few days and remains essentially empty for the rest of the year. We shall return to this important fact below, when we discuss future strategies for grid operation.

Another way of seeing these trends is given in Fig. 3, which presents the daily trends of the ratio of daily surplus PV energy to the corresponding daily solarizable load.

Fig. 3, shows that, for PV sizes below 5 ND, the daily surplus PV energy mostly remains below the daily total solarizable load

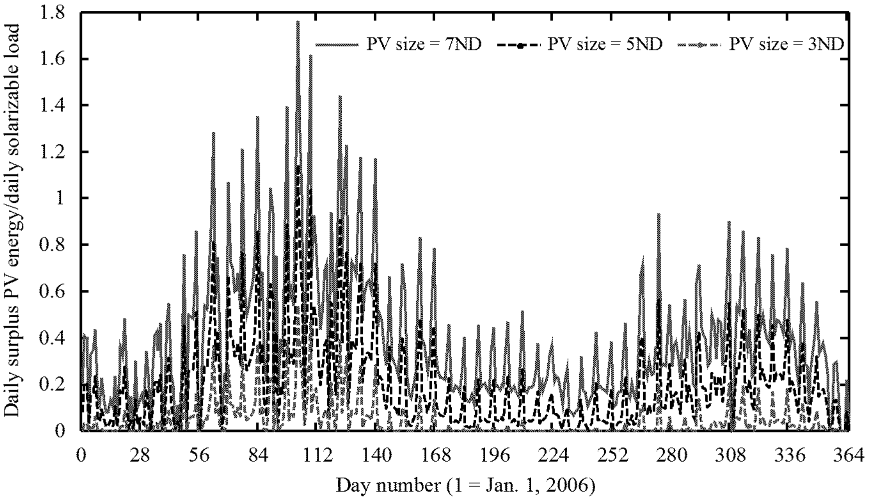

Fig. 3. Daily surplus PV energy as a fraction of daily solarizable load, for ff¼0.7.

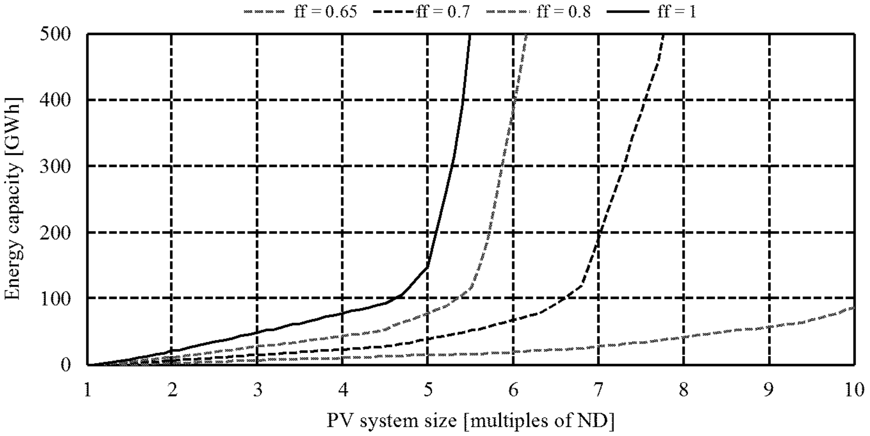

Fig. 4. The trend of annual required energy capactiy with PV system size increase.

(unity on the y-axis). For such a situation the energy stored during a day can be totally consumed during the following night. Therefore, the energy capacity of the required storage is basically determined by the maximum total surplus PV energy produced over a single day. On the other hand, when the PV system size increases to 7 ND the ratio of surplus energy to the corresponding daily solarizable load exceeds unity. In such circumstances, the energy stored during the day cannot be completely discharged during the next night. Consecutive occurrences of such phenomena during the spring period result in a mounting increase of the required energy capacity over this period, which soon empties out when the increased summer demand gets underway. Other grid flexibilities in the range ff¼0.65┐ 1 exhibit qualitatively similar trends.

In addition to considering three specific system sizes on a daily basis as was done above, it is important to see the dependence of the required energy capacity on PV system size on an annual basis. This is shown in Fig. 4, which indicates that the required energy capacity rises almost linearly until the PV system size reaches approximately 5 ND. After that, the required energy capacity rises at an increasingly faster rate. The region of initial linear increase is where energy capacity is determined by peak daily surplus PV energy. On the other hand, the region of sharp increase in energy capacity with PV system size is where energy capacity is determined by daily surplus PV energy plus the sum of the net daily stored energies from the days prior to the one on which the highest peak occurs. Here, the “net daily” stored energy is the cumulative energy that remains in storage after supplying the solarizable load for the previous night.

Fig. 4 shows that the trend is similar for all grid flexibilities considered. However, the slope of increase of the required energy capacity versus the fractional increment in ND size varies. The slope reveals its fastest increase for highly flexible grids but a successively slower increase for grid flexibilities down to ff¼0.65. This changing slope is actually an artifact caused by our use of ND multiples for characterizing PV system size. For the slopes of all curves to be similar the ratio of ND-to-solarizable load would need to remain constant for all flexibilities, which, as was demonstrated in Solomon et al. (2010a, b), is not the case. Had we plotted Fig. 4 using absolute PV system size as the x-axis, all curves would have exhibited almost similar slopes. This point will be elaborated when we discuss power capacity.

The most important lesson to be learned from this subsection is, that for any grid flexibility, the constraint of limiting energy losses to those due to storage inefficiency fixes storage energy capacity according to the PV system size.

3.1.2. Power capacity

We now examine the power capacity requirements of storage systems that correspond to the three system sizes under discussion. For each day of the year there will be one hour for which the change in PV generation takes its maximum value for

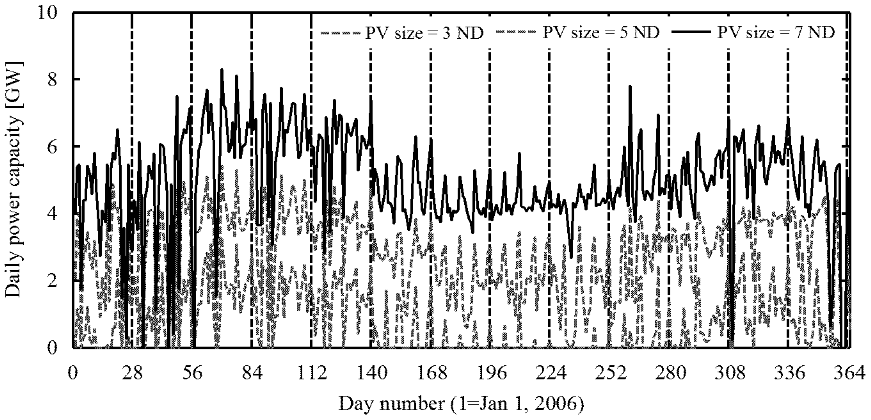

Fig. 5. Daily power capacity requirements of storage for three PV system sizes.

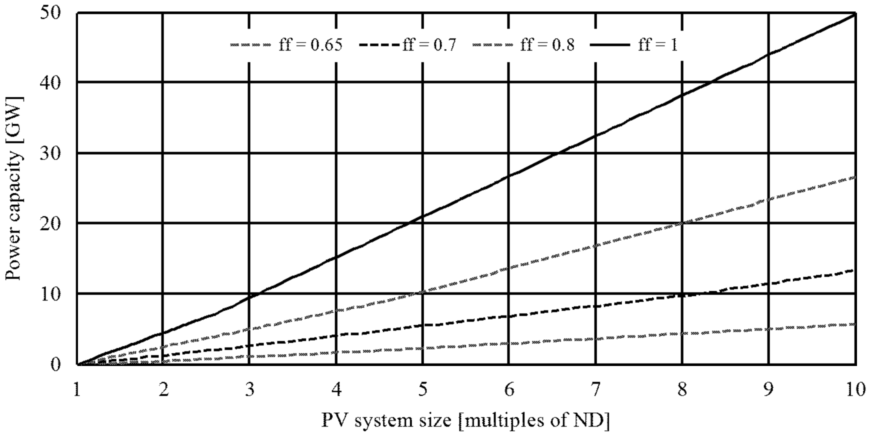

Fig. 6. The trend of annual required power capactiy with PV system size increase at different ff.

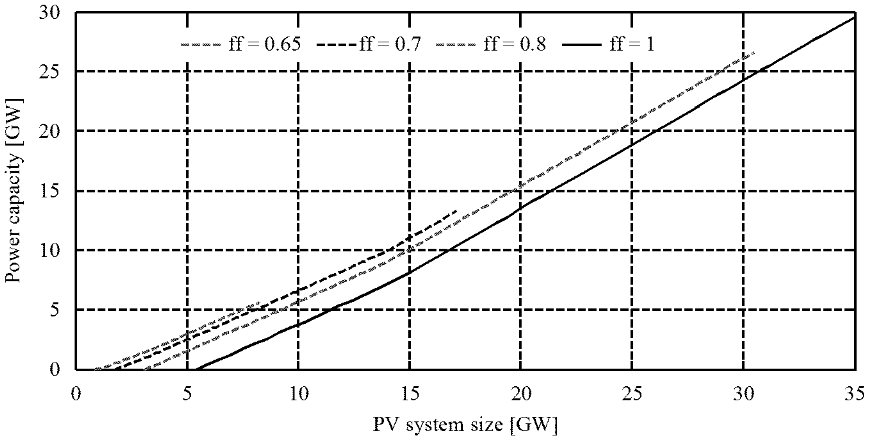

Fig. 7. The trend of annual required power capactiy with PV system size (x-axis in units of GW) increase at different ff.

that day. This maximum determines the storage power capacity requirements for that day. Fig. 5 displays how these requirements are distributed throughout the year.

Just as was seen to be the case for energy capacity, Fig. 5 shows that the maximum daily power capacity requirements for storage also occur mainly in the spring season. As the PV system size is increased, so too are the corresponding power capacity requirements of storage. If no energy losses (other than battery inefficiency) are to be incurred, the required power capacity should be set equal to the spring maximum.

The general trend of required power capacity with PV system size is given in Fig. 6. The figure shows that the required power capacity increases almost linearly with increasing PV system size. The slope of the increase varies monotonically with grid flexibility, showing largest slope for the largest flexibility. It is instructive to re-plot Fig. 6 but with an x-axis corresponding to constant increases in PV system size, rather than in terms of ND size, which itself varies with grid flexibility. Fig. 7 displays the results and shows that in fact the slopes for all grid flexibilities are almost the same. One result of such a re-plot, which might at first glance seem strange, is that the order of the curves is reversed. Namely, whereas for the same ND size the highest grid flexibility requires the highest power capacity for storage, for fixed absolute PV system size it is the lowest grid flexibility that requires the highest power capacity for storage. Corresponding results were found, as stated above, for energy capacity.

Thus far we have presented power capacity results in terms of the charging requirements of storage, as will be the practice for all of the simulations presented in this paper. Clearly, these requirements increase indefinitely as PV system size increases. However, if the charging and discharging properties of storage are identical, then power capacity should in principle be defined in terms of the maximum of the two. The latter, in contrast, is limited by the PV system size and properties of the grid. The following argument will clarify this possible ambiguity and show when each type of definition is heuristically more useful.

For any given PV system size the appropriate power capacity of storage will be determined by the maximum of the hourly charging or discharging requirements. Fig. 8 shows how this composite power capacity depends on PV system size. The y-axis in this figure is actually the ratio of power capacity to maximum discharging requirement. Our singling out of the discharging rather than the charging requirement may at first seem peculiar. But it is easy to see that it is a parameter of great convenience for this discussion. First, if for any given system size, the discharging requirement is less than the charging requirement, then the power capacity will be determined by the latter, and the ratio of power capacity to discharging requirement will be a number greater than unity. On the other hand, if the discharging requirement is greater than the charging requirement, the former will determine the required power capacity of storage. In this situation the ratio of power capacity to discharging requirement equals unity. We may now approach Fig. 8 and immediately realize that for system sizes up to approximately 3 ND it is the discharging requirement that determines the required power capacity for all levels of grid flexibility. (The slight increase in Fig. 8 in the vicinity of 1 ND is of no practical interest because little or no storage is needed in such situations.) For higher system sizes it is the charging requirement that determines the power capacity of the storage: the precise system size at which the change-over occurs depends, as seen in Fig. 8 on the flexibility of the grid.

For small PV system sizes the storage requirements are minimal, with a consequence that an almost empty battery may occasionally be called upon to deliver its entire energy content in a single hour. Therefore, were we to determine the power capacity of storage by its discharging requirement, as the above argument might seem to suggest, the battery would have an unnecessarily large power capacity. In such a situation, it would be more sensible to choose a battery with smaller power capacity and to allow it to discharge into the grid over a larger number of hours without the need to dump any energy. However, care must be taken to ensure that the chosen power capacity is not allowed to be smaller than the peak charging requirement, otherwise PV energy will need to be dumped. For large PV system sizes (which are our main interest because our ultimate aim is to increase grid penetrability as much as possible), the power capacity is defined by the charging requirement as seen in Fig. 8.

Now Figs. 6 and 8 together teach us an important lesson. It will be recalled that the charging and discharging properties of storage have been assumed identical. However, the combined effect of PV system size and load profile lead to considerably different charging and discharging requirements for storage. In order to see this, consider a PV system of size 5 ND. Fig. 8 indicates that the required power capacity (which is the charging capacity in this region of the figure) is approximately 2.5 times larger than the peak discharge capacity of storage. However, Fig. 6 indicates that the required power capacity (which was already defined as the charging capacity) is approximately 20 GW. This implies that the discharge capacity is approximately 8 GW. It will be noticed that this is less than the 9.5 GW peak demand of the IEC grid during the year under consideration. In any event, the planned peak demand for a developing grid system will always place an upper limit on the discharge requirement of storage, and this in turn will be related, via the future equivalents of Figs. 6 and 8 to charging requirements and PV system size.

The most important lesson from this subsection is similar to that for energy capacity. Namely, at any grid flexibility, by limiting energy losses to those incurred by storage inefficiency, the power capacity of storage is determined by PV system size.

3.1.3. Capacity ratio

Having now studied the separate ways in which storage power and energy capacity are constrained to vary with PV system size, it is instructive to examine their interdependence.

Storage systems are often characterized by the ratio: energy capacity/power capacity (Denholm and Margolis, 2007b). In the present paper, we refer to this as capacity ratio (CR), which, in our case, has the units of hours. Fig. 9 displays the dependence of CR on PV system size for a variety of grid flexibility factors ff.

Examining first the curve corresponding to grid flexibility ff¼0.7, which was employed for Figs. 1–3, one sees that Fig. 9

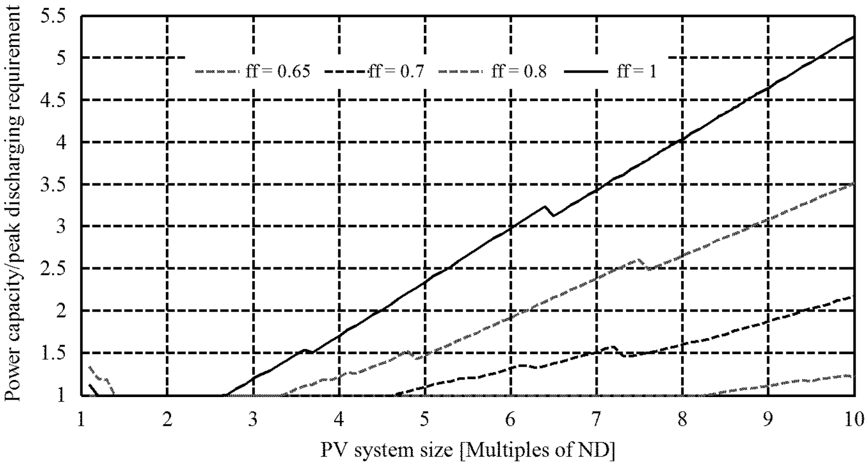

Fig. 8. The variation of power capacity/peak discharging requirements with PV system size.

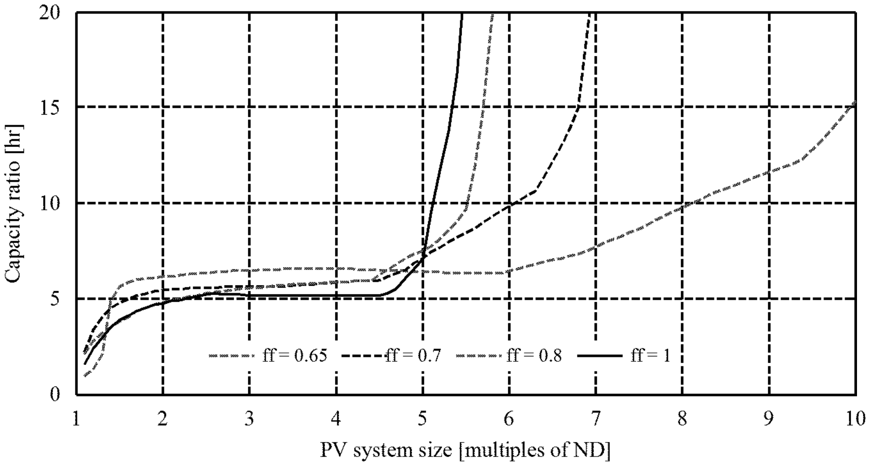

Fig. 9. Capacity ratio of the required storage as function of PV system size for various grid flexibilities.

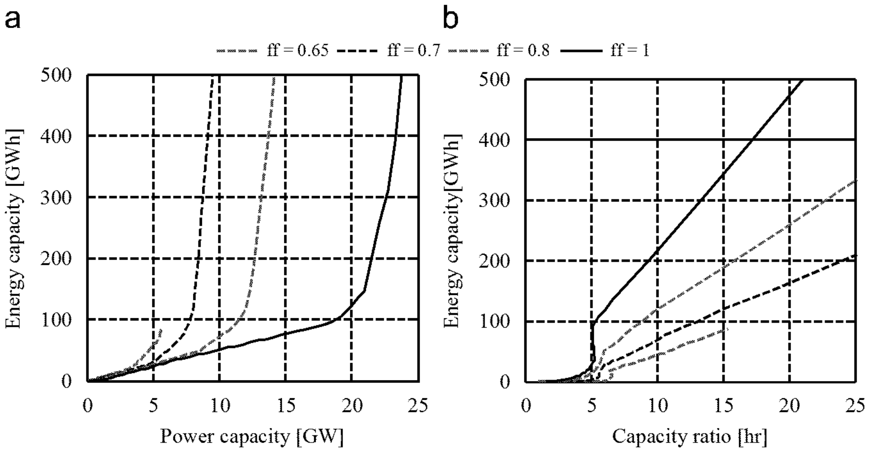

Fig. 10. The dependence of required energy capacity on (a) power capacity and (b) capacity ratio.

reveals three characteristically different regions: (i) There is an initial rise in CR from system size 1 ND, where no storage is needed. This is followed by (ii) a plateau region where CR remains relatively constant, in the approximate range 5 h, for PV system sizes in the range 2–5 ND. This is followed by (iii) a steep rise in CR for larger PV system sizes. The reasons for these three ranges should be clear from our previous discussion: Below 2 ND there is little need for storage since allowing modest amounts of PV energy dumping suffices to inject the bulk of the generated PV energy into the grid (Solomon et al., 2010a, b). The plateau region is where both the required power capacity and energy capacity, as seen in Figs. 4 and 6, show almost linear increases with PV system size. The region of steeply rising CR is caused by a sharply increasing energy capacity (Fig. 4) coupled to a continued linearly rising power capacity (Fig. 6) as PV system size increases further. This overall trend is qualitatively similar for the other flexibilities shown in Fig. 9. We note, in passing, that the curves for all values of grid flexibility (other than ff¼0.65) start to rise steeply for a PV system size close to 5 ND. Had we plotted PV system size in absolute energy units, these changes in slope would each have occurred at a different PV system size. This simplification is another advantage of employing the ND concept.

Further useful information about storage requirements is obtained by plotting energy capacity versus power capacity, as shown in Fig. 10a. Here we see, for any grid flexibility value, an initial linear dependence followed by a steep rise in energy capacity for very little further increase in power capacity. The importance of this observation is that if ones PV system size falls in the initial linear region of Fig. 10a the energy and power capacity of storage are strongly linked to one another. On the other hand, if the PV system size happens to fall in the steeply rising parts of Fig. 10a it is sufficient to choose a convenient value of the power capacity and then increase the energy capacity to any desired value. For example, in the specific case of the 2006 IEC load, for ff¼0.70, a storage system with power capacity └ 7.6 GW can be chosen while increasing the energy capacity to meet the needs of any desired PV system size. For convenience, Fig. 10b plots the CR which corresponds to power capacity for any value of energy capacity that may be of interest.

The important lesson from this subsection is that a relatively narrow range of CR values – typically around 4┐ 6 h – is suitable for a relatively wide range of PV system sizes.

3.2. Storage requirements and grid penetration

The foregoing discussion has shown the various inter-relationships that exist among PV plant size, storage energy requirements, storage power capacity requirements and the ratio of the two later properties. With this knowledge we can now address the matter of grid penetration. Fig. 11 plots grid penetration as a function of the required storage capacity ratio.

Once again, three regions are evident: (i) an initial region of gradual rise in penetration with increasing CR, (ii) a region where

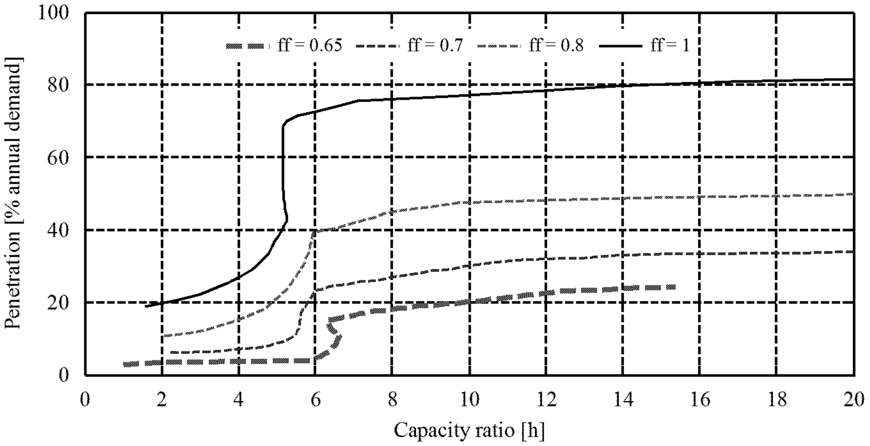

Fig. 11. PV penetration and the capacity ratio of the required storage.

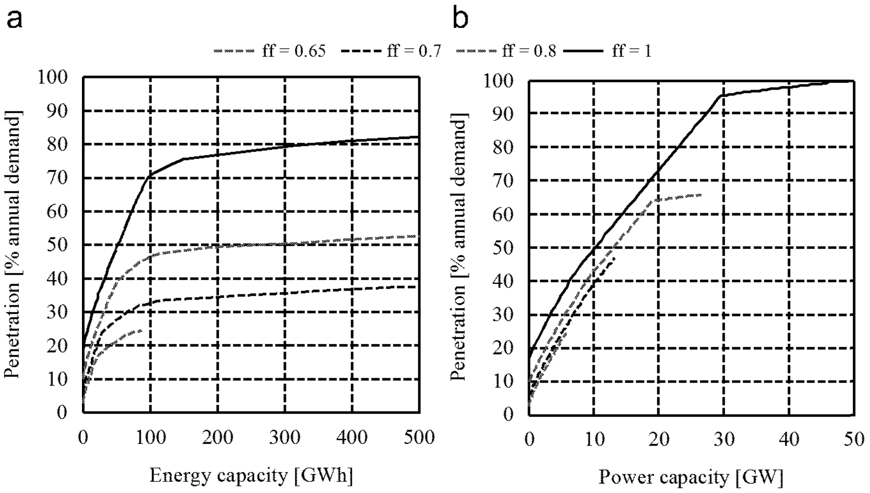

Fig. 12. Dependence of penetration on (a) power capacity and (b) energy capacity.

for a more-or-less constant CR in the vicinity of 5 h, there is a sharp rise in possible grid penetration (up to about 25% for ff = 0.70) and (iii) a plateau region where further increases in CR have a successively diminishing effect in enhancing PV penetration.

The plateau rise in region (iii) of Fig. 11 is a reflection of the sharply rising region in Fig. 9, since large PV penetration requires a large PV plant size. This in turn requires storage with a large energy capacity, but for which, as seen from Fig. 10b, the power capacity is limited.

This trend remains qualitatively similar for all grid flexibilities. In all cases, Figs. 9 and 11 show the onset of a point of diminishing returns in regard to the amount of PV grid penetration that can be achieved by increasing storage size. Clearly, the achievement of 100% penetration of the solarizable load would make unreasonable demands on storage size. It is also clear from Fig. 11 that storage of a given capacity ratio allows significantly different PV penetration levels depending on grid flexibility. It is worthy of note that both the corresponding energy capacity and power capacity requirements vary with flexibility. Accordingly, Fig. 12 presents the dependence of PV penetration on both the power capacity and energy capacity of storage.

From Fig. 12b penetration appears to have an approximately linear dependence on the required power capacity. On the other hand, from Fig. 12a, penetration shows a sharply increasing trend when the energy capacity is small. The penetration rate then starts to level off as we increase storage energy capacity in order to accommodate more surplus PV energy. This indicates that increasing energy capacity far beyond the turning point in Fig. 12a is an increasingly poor strategy, since a small increase in penetration would then require a large increase in the energy capacity of storage. In terms of capacity ratio, as already implied from Fig. 11, the maximum CR should be in the approximate range of 4–6 h, depending upon grid flexibility: any higher value is unnecessarily wasteful in use of storage. The implication is that there is an optimal range of energy and power capacity for storage, linked to one another as shown in Fig. 11, for enhancing grid penetration in an efficient manner.

These results indicate that solarizing the entire solarizable load – using a large storage as defined by constraining PV energy losses to storage inefficiency alone – is not a practical proposition. In fact, even for an ideal grid flexibility of ff = 1, extension of the axes of Fig. 12a would show that for 99.5% penetration we would need storage with energy capacity approximately equal to 50% of the entire annual grid requirements. Comparable unrealistically large energy capacities follow for other flexibilities too.

In all of the above cases, no PV energy dumping was allowed other than the intrinsic losses due to storage inefficiency. The energy loss that is incurred due to storage inefficiency is shown in Fig. 13 as a function of capacity ratio. The figure shows that the loss of PV energy remains less than 14% of annual PV generation even if we choose very large storage with a grid with high flexibility. The maximum possible loss, based on 75% storage efficiency, is obviously 25% but this can happen only if we store all the PV energy and supply the grid entirely

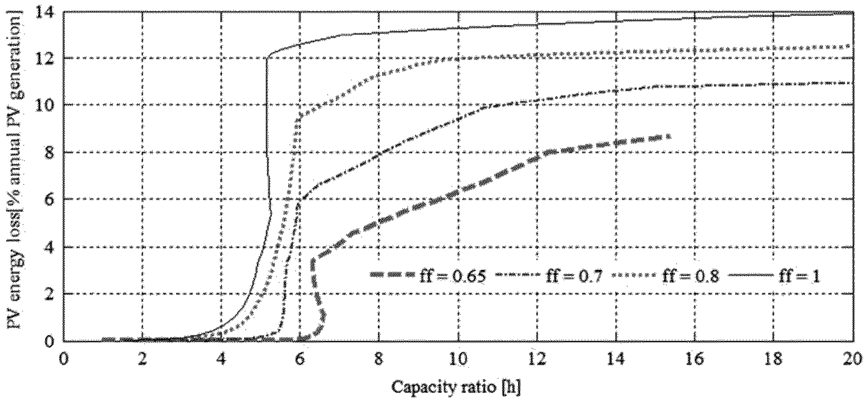

Fig. 13. The PV energy lost due to storage inefficiency.

Table 1
Summary of typical data for storage with approximately 100 GWh energy capacity.

ff	Power capacity (GW)	Capacity ratio (h)	Penetration (% annual demand)	Energy loss (% PV generation)[a]
0.65	5.4	15.4	25	9
0.7	7.3	13.0	32.6	10.4
0.8	10.7	8.6	46.0	11.5
0.9	14.4	7.2	58.9	12.1
1	17.7	5.2	70.2	12.2

[a] Due to storage inefficiency only.

from storage. The actual trend exhibits a lower energy loss mainly because some of the generated PV energy directly enters the grid. On the other hand, the sharp increase in PV energy loss for capacity ratios in the vicinity of 5 h is a consequence of the increasing employment of storage to increase PV penetration. It corresponds to region (ii) described in Figs. 9 and 11. The leveling-off region in Fig. 13 (corresponding to region (iii) in Figs. 9 and 11) indicates that we are utilizing successively less the available storage energy capacity.

The ability of a given storage size to incorporate PV into the grid depends on the grid flexibility. Table 1 presents typical properties for storage of approximately 100 GWh energy capacity, which corresponds to approximately 72% of the average daily demand. From the table, we see numerically the manner in which rising grid flexibility corresponds to falling CR for storage. For grid flexibilities ff Z 0.8, this particular size of storage is close to region (ii) in Figs. 9 and 11. But for lower flexibilities, it falls deeply into region (iii) indicating that 100 GWh of storage is probably oversized for these situations. In particular the corresponding values of CR in Table 1 are very much larger than the range we have already seen that allows efficient PV grid penetration.

The principal lesson from this subsection is that if we limit PV energy losses to those incurred by storage inefficiency, then, depending upon grid flexibility, the annual percentage grid penetration can be increased up to approximately 70% of grid requirements. Beyond that level unreasonably large amounts of storage become necessary.

3.3. Other methods of using storage to increase PV grid penetration

So far we have seen that if we target only the solarizable part of the load, without allowing any dumping of surplus PV energy, storage system performance is limited by the seasonal interaction of PV with the grid. In particular, we have seen that increasing storage size to respond to the large spring seasonal storage demand can do little to increase PV penetration beyond about 25% (for ff¼0.70) of the annual requirements since a large portion of this storage energy capacity remains empty throughout the rest of the year. Indeed, even relatively small storage systems can remain largely un-operational in the summer season. This limitation suggests that we should investigate other strategies for coupling a storage system and its associated PV plant with the grid.

One of the methods that can fulfill this task is to specify the peak energy and power capacity, and to reject any PV surplus energy when it exceeds these peak requirements. This method was adopted by Denholm and Margolis (2007b).

A second one is to follow a strategy based on the seasonal storage requirements. Namely, one employs storage and PV system to reduce the share of baseload plants in the spring season, thus increasing penetration, and dumping some surplus PV energy if necessary. This method can enhance storage system utilization at other times of the year.

A third method, which has less to do with increasing PV penetration than with increasing the utilization of storage during the three seasons when it is severely under-employed for solar purposes, is to store baseload energy during nighttime and use it for peak shaving during the day. In the next section, we will demonstrate how the first two cases will work. We do not address the third method as its employment depends more on internal utility considerations than on solar energy utilization.

3.3.1. Employment of PV energy dumping

In order to demonstrate how this method works, we return to our previous example of a storage battery with a 100 GWh of energy capacity. However, this time we consider its behavior if we allow some PV energy dumping in addition to the intrinsic losses caused by storage inefficiency.

The following three figures show the amount of grid penetration achieved by such a storage system, for three levels of grid flexibility (ff¼0.70, 0.80, 1) and the three values of power capacity in Table 1 (PC¼7.3, 10.7, 17.7 GW). Figs. 14–16 show that if we

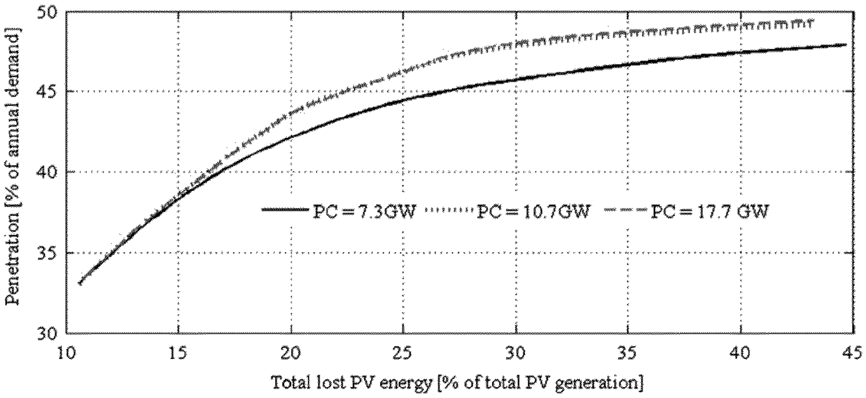

Fig. 14. Grid penetration as a function of total PV energy loss (i.e. storage inefficiency plus dumped energy) for three values of power capacity, for ff¼0.70.

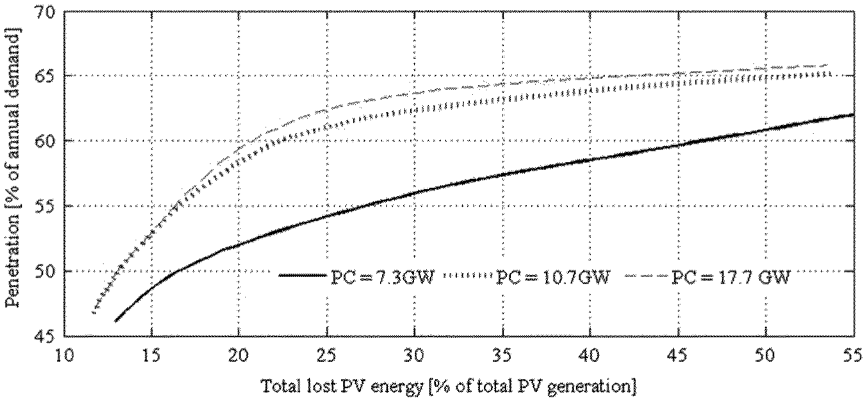

Fig. 15. Grid penetration as a function of PV energy loss (i.e. storage inefficiency plus dumped energy) for three values of power capacity, for ff¼0.80.

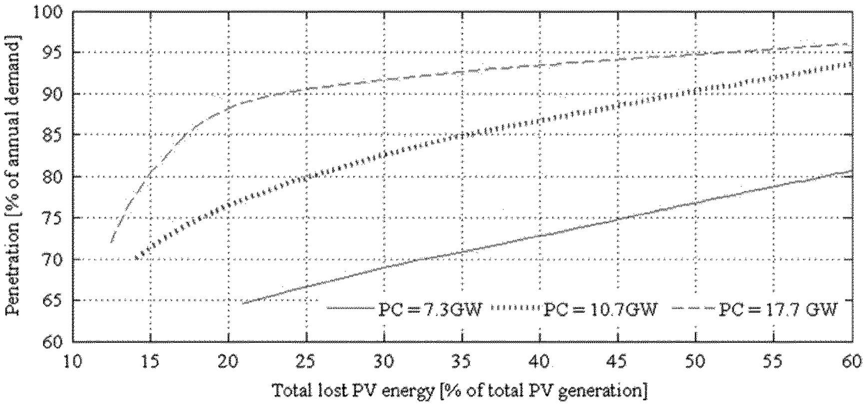

Fig. 16. Grid penetration as a function of total PV energy loss (i.e. storage inefficiency plus dumped energy) for three values of power capacity, for ff¼1.

allow PV energy losses to increase by allowing a small amount of dumping, PV grid penetration increases significantly. This is seen to be true for all flexibilities and for all power capacities. We emphasize the word "small" because as energy dumping is allowed to increase, the advantage is seen rapidly to become marginal.

In Figs. 14–16, each of which represents a single level of grid flexibility, we have drawn grid penetration curves for all three values of power capacity, for purposes of sensitivity, even though only one of these values is appropriate for each level of flexibility. Specifically, Figs. 14 and 15 indicate that for any given level of energy loss that may be deemed acceptable, a large percentage increase in power capacity will lead to a relatively small improvement in grid penetration. On the other hand, Figs. 15 and 16 indicate that if the power capacity of storage is allowed to fall much lower than the calculated value given in Table 1 a serious penalty in grid penetration is incurred. Interestingly, even though these values were calculated for the no energy dumping case, Figs. 14–16 indicate that they must be close to optimal even in situations where energy dumping is permitted. A summary of the quantitative benefits of allowing some PV energy dumping is shown in Table 2, where approximately 10% energy dumping is added over and above the approximately 10% loss due to storage inefficiency—these percentages being relative to total annual PV generation.

It is important to emphasize that if energy losses are restricted to those due to storage inefficiency, in order to reach say 95% grid penetration one would need to employ a massive amount of storage energy capacity, specifically about 6% of the annual grid needs. On the other hand by allowing some dumping, say, 25% total PV energy losses (i.e. approximately 12% due to storage inefficiency and 13% due to dumping), the same percentage penetration can be achieved for a storage energy capacity of only 1% of the annual grid needs (500 GWh). Naturally, a final decision as to which of these strategies for ultrahigh penetration is preferable would depend upon a detailed economic analysis.

Two important lessons emerge from this subsection: first, the inter-relationships among energy capacity and power capacity, caused by limiting energy losses to those due to storage inefficiency continue to remain approximately true when some energy dumping is allowed; Secondly, if we seek ultrahigh grid penetration using storage of any given energy capacity, we need a storage system with high power capacity.

Interestingly, in the study by Denholm and Margolis (2007b), 11 h of storage was found be suitable for achieving a PV penetration of about 50% of the annual demand for a grid with flexibility ff¼0.8. However, although we do not have their data set available, our present study suggests that considerably higher penetration might have been achieved for the same storage energy capacity if a lower CR had been chosen.

3.3.2. Seasonal baseload rescheduling

This method of using storage takes advantage of the observed strong seasonal dependence of PV grid interactions (Fig. 1). In this approach one would shut down some of the baseload plants during the spring season, in order to allow more PV electricity to flow directly into the grid instead of into storage, and also to increase the effective solarizable load at nighttime during this period. This kind of approach, as we shall see, can increase PV penetration still further, and substantially if some dumping of surplus PV energy is allowed.

As an illustration of this approach, we consider a situation in which the baseload had been reduced from 30% of the peak (i.e. the percentage corresponding to grid flexibility ff¼0.70) to 25% of the peak during the 50 spring days over which the required daily energy capacity was more than half the peak annual energy capacity of storage (see Fig. 2). Once again we choose 100 GWh of storage energy capacity for illustrative purposes.

Fig. 17 plots the resulting grid penetration as a function of total lost PV energy (i.e. storage inefficiency plus dumping). One sees that the use of base-load rescheduling increases PV penetration without requiring as much energy loss as in the previously discussed strategy. Specifically, a comparison of Fig. 17 with Table 2 reveals an improvement in annual grid penetration of approximately 2 percentage points for both flexibilities indicated in the figure.

Table 2
Summarizing impact of PV energy dumping from a system with 100 GWh of storage energy capacity.

ff	Power capacity (GW)	Penetration (% annual demand)	
		Loss limited to storage inefficiency alone	Total loss increased to 20% of PV generation
0.7	7.3	32.6 (10.4%)[a]	42.2
0.8	10.7	46.0 (11.5%)[a]	58.6
1	17.7	70.2 (12.2%)[a]	88.5

[a] Percentage of PV generation lost by storage inefficiency.

3.3.3. Baseload rescheduling on a finer time scale

Thus far we have seen that for the same total sacrifice of PV energy, improved grid penetration can be achieved by lowering the baseload level during the spring season. But, in fact, we can do even better. Fig. 18 shows the daily maximum amount of energy in a 100 GWh storage facility for two situations discussed in Section 3.3.2.

Fig. 18 shows, under such circumstance, the maximum daily energy in storage, throughout the year, for the two situations in which (a) no energy dumping is allowed (dotted curve) and (b) where approximately 10% of the PV energy is dumped (piecewise continuous curve). One sees that the dumping of PV energy (i.e. y-axis figures greater than unity) actually occurs on a finer time scale than 50 days. However, nowadays, weather forecasting allows the relatively accurate prediction of "sunny" days on a time scale of several days in advance. This fact, together with the ability of the utility to anticipate overall electricity demands over such periods, could enable the baseload to be readjusted to appropriate levels and lowered during sequences of days when storage is expected to overflow. In this manner, energy dumping could be reduced and in the process, a greater percentage of PV energy would become usable.

3.4. Implications for future grid development

The foregoing discussion leads to a number of important policy implications for future grid development.

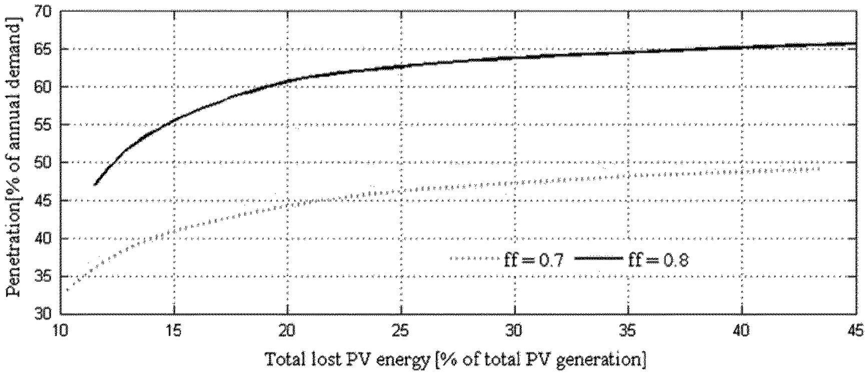

Fig. 17. Grid penetration as a function of total PV energy loss (i.e. storage inefficiency plus dumped energy) when the baseload value in 50 spring days are reduced by 5% of the peak below the value defined for ff¼0.7 and 0.8.

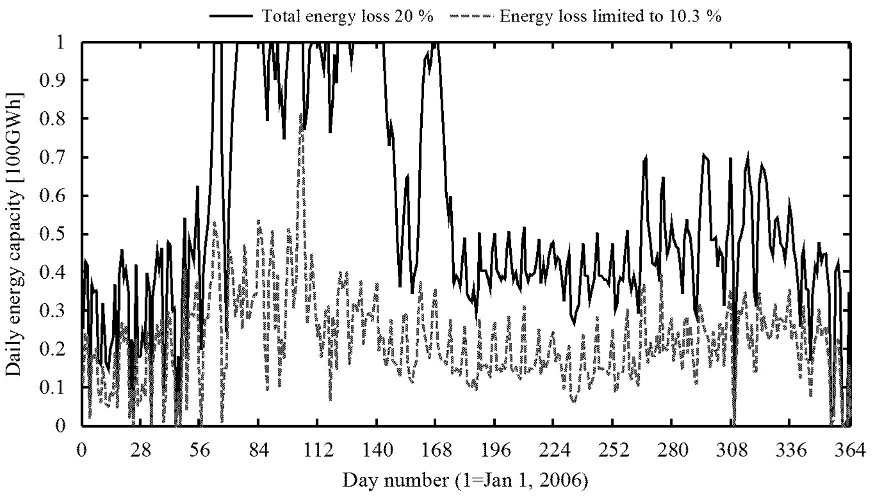

Fig. 18. Maximum daily stored energy, when baseload is reduced by 5% during 50 spring days for (a) zero energy dumping (dotted) and (b) approximately 10% energy dumping (continuous).

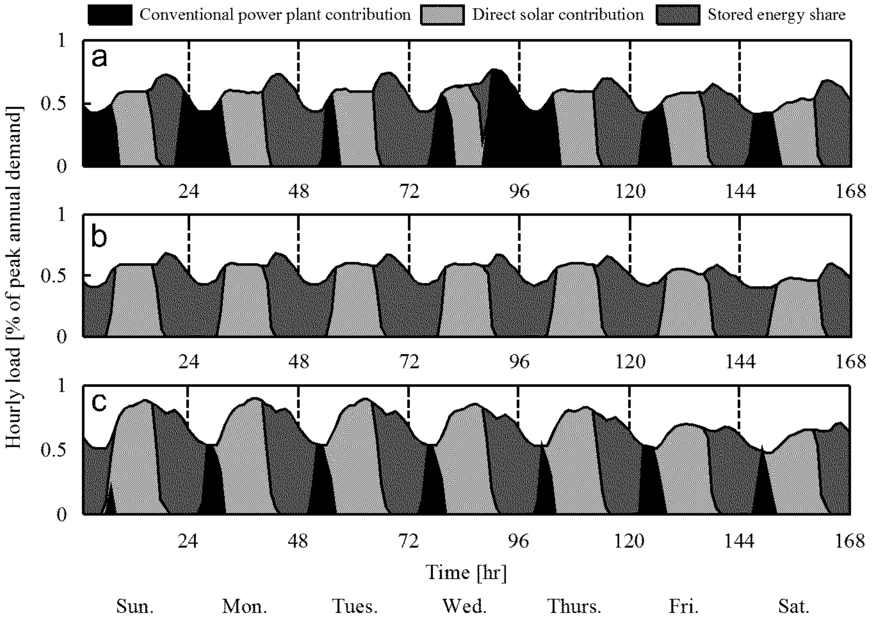

Fig. 19. Simulated contributions to the IEC daily demand from PV (pale grey), storage (dark grey) and fossil plants (black), for (a) January 2–8, (b) March 20–26, (c) July 3–9, 2006. Assumes ff¼1, 100 GWh storage energy capacity, 17.7 GW charging power capacity and 9.5 GW discharging capacity (¼peak demand), and 20% total energy loss (of which approximately 12% is due to storage inefficiency and 8% is dumped energy). This combination would have provided 89% of the annual grid requirements.

First, if the energy capacity of storage is large enough, typically 100 GWh in the case of the IEC grid in 2006 (which was 72% of the average daily demand), and its power capacity is appropriately sized, grid flexibility can become effectively unity because storage has the capability to provide for 100% of the load during certain times of the year. This point can be seen in Fig. 19, which shows the respective contributions to the daily load from PV, storage and conventional power plants, for 3 typical weeks during the year 2006. In Fig. 19, the solar contribution is indicated in pale grey, the storage contribution is in dark grey, and the fossil-plant contribution is in black.

Fig. 19 clearly shows that during the spring week, PV and storage provide 100% of the total load, i.e. grid flexibility is indeed unity (and in fact irrelevant). On the other hand, during the winter and summer weeks, the employment of fossil fuel becomes minimal.

The second implication is that whatever storage energy capacity is deemed appropriate, it is of vital importance for storage to have an appropriately large charging capacity and discharging capacity: the former being determined by the PV-grid interaction and the latter being determined by the maximum load.

A third implication is the importance of accurate weather and load profile forecasting for periods up to approximately 1 week. This will enable the power company to predict the time-dependence of the energy in storage and to make appropriate decisions regarding the dispatch of conventional power plants.

A fourth implication that arises from the existence of a large PV-storage grid component, is that since there is little or no requirement for fossil input, large thermal plants, such as the coal-fired variety, which have comparatively long startup and shutdown times, will have progressively less use in a future grid system.

A fifth, related, implication is that the backup requirements for a largely PV-storage fed grid system, should come from quick startup, fast-ramping plants. Note however, that in contrast to the latter's present use for peak demand, in a future grid they will serve mainly for late-evening/early morning, low-demand periods as seen in Fig. 19a, c.

Finally, it is important to keep in mind that Fig. 19 represents a "prediction" after the fact. In a real situation, the employment of accurate forecasting will enable a grid operating strategy that obviates the need for a large percentage of the existing fossil-fueled plants. Their existence means that the grid will be able to grow to meet future demands without the need to build further fossil-based plants. In the case of the 2006 demand, Fig. 19 illustrates how PV and appropriate storage could have provided 89% of the annual demand. The precise sizing of the three grid components: PV, storage, fossil-backup capacity, in a future grid, will require further study. For example, the storage system will need to be capable of providing a number of parallel functions such as, power control, load-following, long-term energy storage, etc. This will probably require storage to be composed of a variety of technology types.

4. Conclusions

In the present study we have employed a specific data set (namely that of the Israel Electric Corporation for the year 2006) of hourly grid load data, and corresponding predictions of a solar power plant in order to study the manner in which storage with appropriate properties can improve the grid penetration of "very large" (i.e. larger than what we had previously referred to as "no-dump") PV systems.

The first major finding of the present study was a number of intrinsic relationships that exist between the energy capacity (EC) and power capacity (PC) of the required storage, PV system size, and grid properties. We found that by imposing the constraint that no PV energy is lost, other than that due to storage inefficiency, there is a resulting linkage between EC, PC and PV system size. This linkage is of a form that for any given grid flexibility, EC and PC vary approximately linearly with one another, both increasing as PV system size increases in the approximate range 2┐ 5 ND. For larger PV system sizes, the increase in EC is far more rapid than that of PC.

A second important finding, that is true for all levels of grid flexibility, is one that enables us to identify the appropriate size of PC for any given PV system size. Specifically, for all system sizes it is the charging requirement that defines the power capacity of storage. However for very large storage sizes, typically 100 GWh in the case of the IEC grid, it would be desirable to size the discharge capability of storage to equal or slightly exceed the maximum expected hourly load.

Our third important result pertains to the enhancement of PV grid penetration. We found that as storage size increases initially (i.e. in the range where EC and PC are linearly linked), there is a quite substantial rise in grid penetration. However, further increases in EC – beyond the initial range – exhibit a diminishing ability to enhance grid penetration. A practical result of these last two findings is that in order to achieve large-scale grid penetration in an energy-efficient manner, the optimal value of CR should be in the range 4–6 h (depending on grid flexibility).

A fourth important finding was that properly designed storage, with any given EC, needs to have an appropriately high PC (i.e. low CR) if it is to operate efficiently with a grid of high flexibility.

These newly discovered linkages among the properties of storage were subsequently employed in order to study various strategies for increasing the grid penetrability of very large PV systems. Specific strategies that were studied included: fixing the storage size (both EC and PC) and allowing some PV energy dumping; changing baseload scheduling on a seasonal basis and on a shorter time scale (e.g. a few days). These strategies led to three important findings:

(i) that if a modest amount of energy dumping is allowed, the previously discovered linkage between EC and PC remains the best strategy for maximizing grid penetration, and that furthermore, penetration is increased in a significant manner. Conversely, choosing storage properties in a manner that fails to observe the required linkage between PC and EC can result in a very inefficient storage system, i.e. one that is larger than necessary, remains mostly empty for long periods of time, and provides less grid penetration than could otherwise be achieved;
(ii) that allowing modest energy dumping is, in itself, a good strategy to avoid the need for excessively large storage and
(iii) that the use of seasonal rescheduling of baseload plants, together with appropriately expanded forecasting (which includes expected solar availability, stored energy, in addition to all of the other characteristics that utilities normally consider for plant scheduling), leads to the highest levels of penetration, to a more efficient use of storage and to less energy dumping.

Among the many simulations we performed using these strategies we found that at high grid flexibilities (in the range ff¼0.8–1), PV grid penetration levels in the range 60┐ 90% of annual requirements could be possible.

A related consequence is that, in the future, with appropriately designed storage and accurate forecasting of both load profiles and weather patterns, it will be possible to operate the grid at a flexibility ff¼1. At such time, coal-fired power plants will have no further use, all backup requirements being provided by quick-start, fast-ramping power plants.

All of these findings underline the importance of designing storage in a manner that takes fully into consideration the interaction between PV and the grid system. Appropriate design in this manner plays a decisive role in the ability of storage to increase grid penetration.

Naturally, in any specific situation the economic implications of these strategies would need to be evaluated.

Finally, although our study employed a very specific data set, a number of features will certainly be qualitatively true for wider situations. First, the no additional losses (other than storage inefficiency) constraint will provide a mathematical linkage between PC and EC of storage for any grid profile and associated solar profile. That linkage will then enable the optimal choice of storage to be made—probably also, as in our situation, if this strict constraint is relaxed somewhat. Furthermore, the major requirement of storage in springtime is a feature that is probably not unique to Israel. Therefore, several of the specific conclusions we have drawn regarding the optimal employment of storage for the Israeli grid should remain approximately true for other locations. In any event, the results presented in the present paper provide a check list of features that will help optimal calculations to be made elsewhere.

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Appendix I. Storage system calculations

In order to avoid several pages of unnecessary repetition, this appendix is a continuation of Appendix B in our first paper (Solomon et al., 2010a); the present equations being numbered sequentially following those previously presented.

So far the algorithm we have developed only evaluates the ability of PV energy to match the solarizable part of the demand that coincides with the actual time of PV generation. However, PV energy can also be used to supply the demand at later times if the surplus PV energy is stored.

We accordingly need to investigate how the storage system size requirement varies as successively more surplus energy is generated by the PV system. As stated in the main text, we shall assume that the only energy loss is due to storage inefficiencies. Such an assumption is useful in order to clarify how a storage system may improve the grid penetration of PV energy, and factors that limit the role of a storage system to perform this task. The following algorithm evaluates the energy capacity and power capacity of the storage required to store the surplus energy generated by a given PV system size. For our purpose, it is sufficient to characterize the storage system by its charging efficiency, η_c, and discharging efficiency, η_d.

We first modify the matrix Q (Eq. (B4)), which represents the PV system size, and create a more general matrix Q1, by replacing ND by ND_{ff_j}, the ND size evaluated for a solarizable load corresponding to grid flexibility ff_j (note that $ND_{ff_j} > 0$):

$$Q1 = ND_{ff_j} \times \begin{bmatrix} 1 & 1+m & 1+2m & \cdots & \cdots & 1+km \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 1+m & \cdots & \cdots & \cdots & 1+km \end{bmatrix}. \quad (B18)$$

Then, a matrix P, equivalent (Eq. (B6)), which represents the hourly output of our larger-than-ND PV system, is defined by the Hadamard product:

$$P2 = Q1 \circ P1. \quad (B19)$$

Lastly, corresponding to the matrix T (Eq. (B7)), we define a modified matrix T1, which represents the solarizable part of the load delivered by the conventional grid plants for grid flexibility ff_j:

$$T1 = \begin{bmatrix} t_1 & t_1 & t_1 & \cdots & \cdots & t_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ t_{8760} & t_{8760} & \cdots & \cdots & \cdots & t_{8760} \end{bmatrix}. \quad (B20)$$

(The difference between Eqs. (B7) and (B20) is that the matrix elements of the former represent total hourly grid loads, whereas those of the latter represent only the solarizable parts.)

The matrix $A1 = P2 - T1$ then represents the "attempted" hourly PV input into the grid for this specific PV system size and grid flexibility.

We now define the following logical matrices that will help identify the potential hourly stored energy and the potential hourly solarizable load to be supplied by the stored energy if available. Logical matrices H1 and W are defined as

$$H1_{i,j} = \begin{cases} 1 & \text{if } (A1_{i,j} \geq 0), \\ 0 & \text{if } (A1_{i,j} < 0), \end{cases} \quad (B21)$$

$$W_{i,j} = \begin{cases} 1 & \text{if } (A1_{i,j} < 0), \\ 0 & \text{if } (A1_{i,j} \leq 0). \end{cases} \quad (B22)$$

The amount of hourly stored energy that is in the storage is then given by a matrix S each element $S_{i,j}$ of which represents the energy stored at time i (for the jth incremental step in PV system size). To determine the general matrix S, first we assume that we have an empty storage at time $t=0$. Thus, the matrix element at $i=1$ is zero (S_1,0). For all other i, we use the following algorithm:

$$\begin{aligned} S_{i,} = {} & a_{i-1} \circ S_{i-1,} \circ H1_i + \eta_c (A1_i \circ H1_i) + \frac{A1_i \circ W_i \circ d_i}{\eta_d} + a_{i-1} \circ S_{i-1} \circ d_i \circ W_i \\ & + \eta_d (a_{i-1} \circ S_{i-1,} \circ z_i \circ W_i) + A1_i \circ W_i \circ z_i, \end{aligned} \quad (B23)$$

where the vectors a_{i-1}, d_i and z_i are

$$a_{i-1} = (S_{i-1,} \geq 0)$$

$$d_i = \left(S_{i-1,} \times a_{i-1} \geq -\frac{A1_i \circ W_i}{\eta_d}\right), \text{ and}$$

$$z_i = \left[\frac{a_{i-1} \circ S_{i-1,j} \circ W_i}{\eta_d} < -W_i \circ A1_i\right], \quad (B24)$$

respectively.

The six terms in the Eq. (B23) represent, in sequence:

- a previously stored amount of energy;
- newly generated surplus PV energy to be stored;
- the maximum amount of stored energy that is to be withdrawn in order to meet the unmatched solarizable load (i.e. in situations when the amount of stored energy exceeds that part of the solarizable load which cannot be provided directly by PV—hereafter, the "unmatched part");
- total stored energy available for withdrawal corresponding to the situation in the previous term;
- stored energy withdrawn in order to supply only part of the unmatched solarizable load (i.e. when the stored energy is less than the unmatched solarizable load) and
- the unmatched total solarizable load (which may be fully or partly matched if the value of the fifth term is greater than zero).

The last term in Eq. (B23) indicates that such a condition requires that the conventional grid system must make up for any shortfall that is not met by either direct PV or stored PV energy.

Of the six terms in Eq. (B23): the first two describe situations in which, surplus PV generation is placed in storage; the second two terms describe situations in which there is sufficient energy in storage to provide for all of the unmatched part of the solarizable load; the last two terms describe situations in which backup must be used because there is not enough energy in storage.

The logical matrices used in this equation require that if any of the above pairs of terms is non-zero, the remaining four terms vanish.

The matrix S contains all necessary information about the system. For example, it can be employed to calculate the energy capacity and power capacity of the storage required for a given PV system size, as follows:

Energy capacity

The maximum hourly stored energy observed for a given PV system size and grid flexibility then indicates the minimum required storage energy capacity that effectively transfers the unmatched PV energy to other times. The required energy capacity (E) to store the surplus energy generated by a given PV system size that is coupled to a grid system with flexibility ff_j is

$$E = \max(S_j), \tag{B25}$$

where $\max(S_j)$ is the largest element of vector S_j.

Power capacity

Power capacity is the maximum amount of energy that can be injected into or withdrawn from storage during a single hour. To calculate the power capacity, we first perform the following computation.

Define a new logical matrix "L1":

$$L1_{i,j} = \begin{cases} 1 & \text{if } (S_{i,j} \geq 0), \\ 0 & \text{if } (S_{i,j} < 0). \end{cases} \tag{B26}$$

The available stored energy matrix is then $S1 = L1 \,|\, S$. Now define a new matrix Z:

$$Z_i = S1_{i+1} - S1_i. \tag{B27}$$

The matrix Z thus contains the hourly charging or discharging requirement for the storage, defined by the mutual interaction of PV, grid and storage. In general this matrix contains both positive values, representing the charging requirement of storage over the time $t' = i+1$, and negative values, representing the required discharging capacity. The power capacity (PC) of the required storage for a given PV system size that is coupled to a grid system with flexibility ff_j is therefore

$$PC_j = \max(\text{absol}(Z_j)), \tag{B28}$$

where $\max(\text{absol}(Z_j))$ is the maximum value found among the absolute values of the vector components Z_j. However, this method has been found to lead to an unnecessarily large power capacity, at least in some cases as discussed in the main body of this paper, especially when the power capacity is defined by discharging requirement. We accordingly define a matrix algebra that will enable us to separate both components and define the power capacity by charging capacity alone.

We define two logical matrices J1 and K1 as shown below:

$$J1_{i,j} = \begin{cases} 1 & \text{if } (Z_{i,j} > 0), \\ 0 & \text{if } (Z_{i,j} \leq 0), \end{cases} \tag{B29}$$

$$K1_{i,j} = \begin{cases} 1 & \text{if } (Z_{i,j} \leq 0), \\ 0 & \text{if } (Z_{i,j} > 0). \end{cases}$$

Then $CQ = J1 \,|\, Z$ is a matrix whose ith row gives the charging capacity requirement of the storage at the i+1th hour of the year. Similarly, the matrix $DQ = K1 \,|\, Z$ gives the corresponding discharging requirements (whose value is less than zero). Hence a more useful measure of the power capacity will be

$$PC_j = \max(CQ_j). \tag{B30}$$

In the absence of specific information about the storage system—as in the current paper, one can use a round trip efficiency, η, as representative of storage efficiency. In such a case, the above algorithm can be simplified by setting $\eta_c = 1$ and $\eta_d = \eta$, or vice versa. Moreover, some of the six terms in Eq. (B23) and their corresponding logical matrices will not be needed.

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ATTACHMENT 7

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Grid flexibility and storage required to achieve very high penetration of variable renewable electricity

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abstract

We examine the changes to the electric power system required to incorporate high penetration of variable wind and solar electricity generation in a transmission constrained grid. Simulations were performed in the Texas, US (ERCOT) grid where different mixes of wind, solar photovoltaic and concentrating solar power meet up to 80% of the electric demand. The primary constraints on incorporation of these sources at large scale are the limited time coincidence of the resource with normal electricity demand, combined with the limited flexibility of thermal generators to reduce output. An additional constraint in the ERCOT system is the current inability to exchange power with neighboring grids.

By themselves, these constraints would result in unusable renewable generation and increased costs. But a highly flexible system – with must-run baseload generators virtually eliminated – allows for penetrations of up to about 50% variable generation with curtailment rates of less than 10%. For penetration levels up to 80% of the system's electricity demand, keeping curtailments to less than 10% requires a combination of load shifting and storage equal to about one day of average demand.

1. Introduction

There are three main technology pathways for supplying large amounts of low-carbon electricity—nuclear, fossil with carbon capture and sequestration (CCS), and renewables. Each option has challenges—CCS and nuclear have problems of scale-up, and waste disposal (plus limits in their ability to perform load-following). Renewables, particularly wind and solar are challenged by the variability of the resource. While the "cost-optimal" solution may require all three (including dispatchable renewables such as hydropower, biomass, and geothermal) it is informative to examine the "limiting case" of a variable renewable-dominated scenario. This will provide insights into the changes to the grid required if powered mostly by variable sources.

In the US, the limits of wind and solar are not resource based—the wind and solar resource are significantly greater than the total electric demand (US DOE, 2008; Denholm and Margolis, 2008a). The primary technical challenge is the variability of the resource (sometimes referred to as intermittency) or the fact that the supply of variable renewable generation does not equal the demand for electricity during all hours of the year. Recent growth of renewables has prompted many integration studies, which in the US have examined the costs and impacts of deploying increasing amounts of wind and solar penetrations on the grid. Examples include the Eastern Wind Integration and Transmission Study (EnerNex, 2010), which examined the impacts of meeting up to 30% of the eastern US electricity demand from wind, and the Western Wind and Solar Integration Study which examined the impact of up to 35% wind and solar on a part of the western US grid (GE Energy, 2010). A summary of wind integration practices and studies is provided by Ackermann et al. (2009), Corbus et al. (2009), and DeCesaro et al. (2009). These studies have found that these levels of variable generation (VG) can be accommodated by certain operational changes, such as greatly increasing the size of balancing areas and cooperation between utilities to maximize diversity of the wind resource and demand patterns. Technically, this requires substantial new transmission additions, but does not absolutely require large-scale deployment of certain enabling technologies such as energy storage to maintain reliability. These studies also demonstrate the increasing challenges to integration of wind energy that may result from the limited coincidence of wind energy supply and consumer demand patterns, combined with the inflexibility of conventional generators. At higher penetration of wind and solar, this combination results in potentially excess wind and solar generation, resulting in curtailed output and higher overall costs. However, the effects of variability at penetration beyond 30% in the US are not well studied, so the

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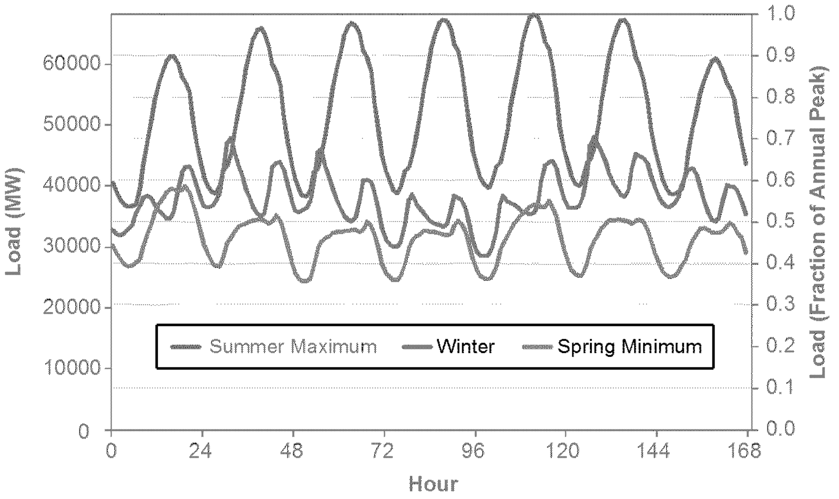

Fig. 1. Hourly loads from ERCOT in 2005.

need for flexibility and enabling technologies such as energy storage at extremely high penetration of VG are not well quantified.[1]

This analysis differs from wind integration studies that evaluate the technical feasibility, or operating costs of a small number of wind penetration scenarios, based on current or near future grid conditions and using detailed grid production simulations. Instead, it examines in general what changes to the grid would be necessary to accommodate extremely high penetration of variable renewables in terms of system flexibility, and the potential role of enabling technologies such as energy storage. This analysis is part of a much larger study by the US Department of Energy (Renewable Electricity Futures) to examine the system-level requirements of deriving the majority of the nation's electricity from renewable energy sources. The larger study examines the economic and technical impacts of various mixes of renewables across the entire US at a seasonal to hourly level.

The analysis in this study focuses on a single isolated region (the Texas grid in the US) and a mix of renewables dominated by solar and wind to examine a "limiting case" where the grid is dependent on variable renewables as opposed to dispatchable renewables such as biomass or geothermal. This report analyzes scenarios where VG provides up to 80% of the system's electricity, which is a somewhat arbitrary target, but also based on estimates that carbon reductions of about 80% will be required for climate stabilization, and corresponds to emissions reductions in recent proposed legislation (US EPA, 2010). This scenario will provide insight into the flexibility requirements, including energy storage, which may be needed in a grid dominated by variable renewable sources.

We begin by examining some general characteristics of electric power systems focusing on system flexibility, or the ability of conventional generators to vary output and respond the variability and uncertainty of the net load. We then provide a description of a tool (REFlex) that we developed to evaluate the interaction between variable generation and normal electricity demand patterns, considering the limitations of the flexibility of traditional electric generators. Next, we provide results of several simulations that estimate the amount of curtailed VG[2] in scenarios where VG provides up to 80% of the total electricity demand. Finally we examine the reduction in curtailment that results when enabling technologies such as energy storage are deployed.

2. Challenges of extremely high penetration of variable generation

2.1. Current operation

Reliable electric power system operation requires a mix of power plants that can respond to the constantly varying demand for electricity as well as provide operating reserves for contingencies. Fig. 1 illustrates an example demand pattern for three weeks for the Electric Reliability Council of Texas (ERCOT) grid during 2005 (see Section 3.1 for additional discussion of the ERCOT grid). This demand is met with three types of plants typically referred to as baseload (meeting the constant demand), intermediate load (meeting the daily variation in demand), and peaking (meeting the peak summertime demand).

In addition to meeting the predictable daily, weekly, and seasonal variation in demand, utilities must keep additional plants available to meet unforeseen increases in demand, losses of conventional plants and transmission lines, and other contingencies. This class of responsive reserves is often referred to as operating reserves and includes meeting frequency regulation (the ability to respond to small, random fluctuations around normal load), load-forecasting errors (the ability to respond to a greater or less than predicted change in demand), and contingencies (the ability to respond to a major contingency such as an unscheduled power plant or transmission line outage) (NERC, 2009). Both frequency regulation and contingency reserves are among a larger class of services often referred to as ancillary services, which require units that can rapidly change output.

2.2. Impact of variable generation

Variable renewable generators (primarily wind, solar photovoltaics, and concentrating solar power when deployed without storage) are unlike conventional generators. They cannot be dispatched (except by curtailing output) and their output varies depending on local weather conditions, which are not completely predictable. Variable generators reduce the fuel (and associated

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[1] Several European studies have examined higher penetrations, and found that the amount of wind curtailment, and need for technologies such as energy storage depend greatly on the mix of generators, access to spatially diverse resources and ability to share generation and load with a large interconnected network (Ackermann et al. 2009, Tuohy and O'Malley, 2009).

[2] From this point on, variable renewable generators will be referred to as variable generation (VG) following NERC (2009).

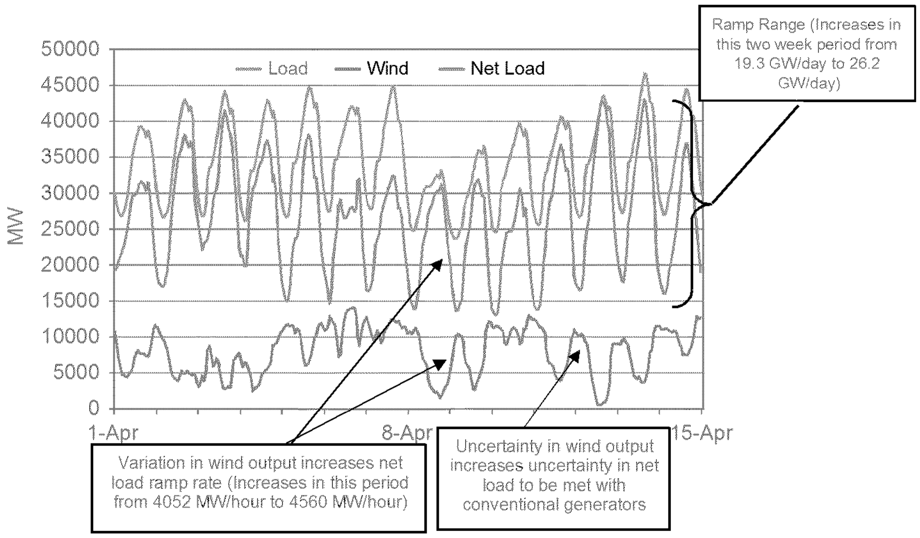

Fig. 2. Impact on net load from increased use of renewable energy.

emissions) from load-following and cycling units and in order to be of benefit, conventional generators used to meet the normal demand must be able to reduce output and accommodate wind and solar generation.

Fig. 2 illustrates a simplified framework for understanding the impacts of variable renewables, where VG reduces the net load met by conventional generators. In this figure, renewable generation is subtracted from the normal load, showing the "residual" or net load that the utility would need to meet with conventional sources.[3] There are four significant impacts that change how the system must be operated and affect costs. First is the increased need for frequency regulation, because wind can increase the short-term variability of the net load (not illustrated on the chart). Second is the increase in the ramping rate, or the speed at which load-following units must increase and decrease output. The third impact is the uncertainty in the wind resource and resulting net load. The final impact is the increase in overall ramping range – the difference between the daily minimum and maximum demand – and the associated reduction in minimum load which can force baseload generators to reduce output, and in some cases force the units to cycle off during periods of high VG output. Together, the increased variability and uncertainty of the net load requires a greater amount of flexibility and operating reserves in the system, with more ramping capability to meet both the predicted and unpredicted changes in net load.[4]

Previous wind integration studies in the US have focused primarily on the operational feasibility and integration costs due to the increased variability and uncertainty in net load where VG provides up to 30–35% of total demand. General approaches to address variability and uncertainty while maintaining reliability at these levels of penetrations are discussed by NERC (2009, 2010). At higher penetrations, a primary constraint becomes the simple coincidence of renewable energy supply and demand for electricity, combined with the operational limits on generators providing baseload power and operating reserves. This may present an economic upper limit on variable renewable penetration without the use of enabling technologies.

2.3. System flexibility

System flexibility can be described as the general characteristic of the ability of the aggregated set of generators to respond to the variation and uncertainty in net load. At extremely high penetration of VG, a key element of system flexibility is the ability of baseload generators, as well as generators providing operating reserves, to reduce output to very low levels while maintaining system reliability.

Fig. 3 illustrates this issue by providing the impacts of system flexibility and generator minimum load on accommodating VG. These two charts superimpose a spatially diverse set of simulated wind and solar data on load data from the same year (the data sets are discussed in detail in Section 3). In the first simulation (left chart), it is assumed that thermal generators are unable to cycle below 21 GW or 65% below the annual peak load of about 60 GW. In this case a mix of wind and solar provides 20% of the energy demand. However, 21% of the VG generation must be curtailed due to the minimum generation constraints caused by baseload units that are unable to cycle, or thermal units that cannot be turned off because they are providing operating reserves to accommodate the increased ramp rates and uncertainty of the net load. The right graph shows the result of increasing flexibility, allowing for a minimum load point of 13 GW. Curtailment has been reduced to less than 3%, and the same amount of variable renewables now provides about 25% of the system's annual energy.

Minimum generation constraints (and resulting wind curtailment) are already a real occurrence in the Danish power system, which has a large installed base of wind generation (Ackermann et al., 2009). Due to its reliance on combined heat and power electricity plants for district heating, the Danish system needs to keep many of its power plants running for heat. Large demand for heat sometimes occurs during cold, windy evenings, when electricity demand is low and wind generation is high. This combination sometimes results in an oversupply of generation, which forces curtailment of wind energy production. It should be noted

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[3] This figure uses ERCOT load data from 2005 along with 15 GW of spatially diverse simulated wind data from the same year. See Section 3 for more details about the data used.

[4] There are additional technical challenges associated with VG integration such as the potential decrease in mechanical inertia that helps maintain system frequency. This challenge is not well understood and could be mitigated by a variety of technologies including improved controls on wind generators, or other sources of real or virtual inertia that could include energy storage (Doherty et al., 2010).

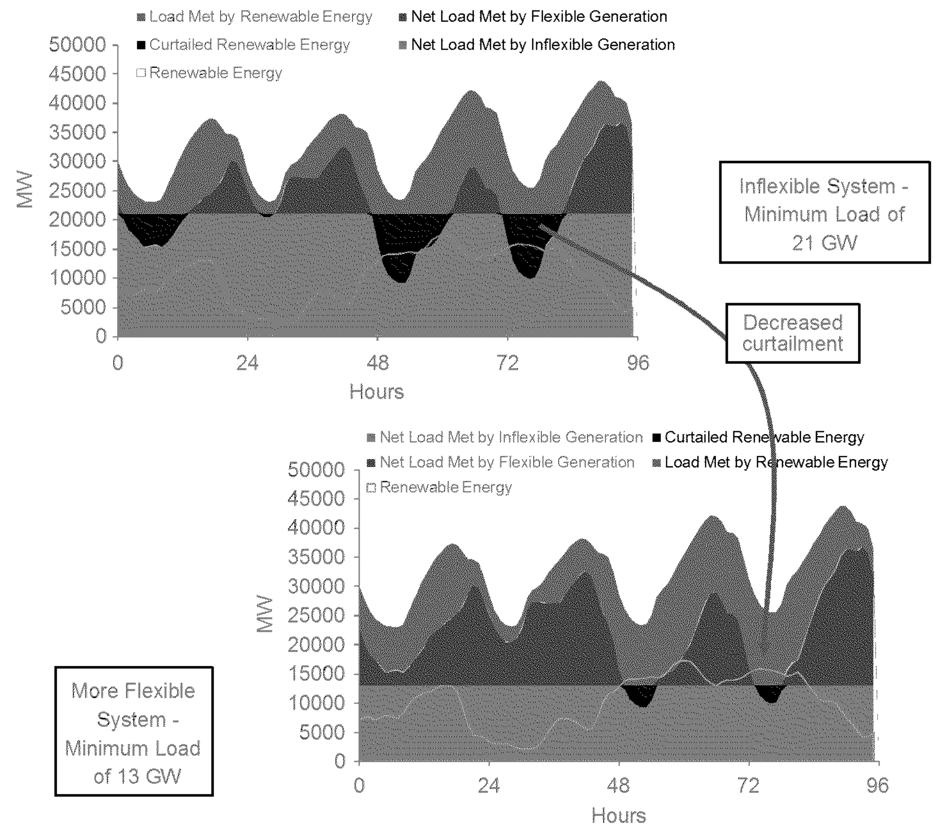

Fig. 3. Impact of system flexibility on curtailed energy.

that wind curtailment also occurs in the US grid, primarily due to transmission constraints (Fink et al., 2009). The best example is in Texas, where insufficient transmission from West Texas to load centers in East Texas resulted in curtailment of 17% of wind generation in 2009 (Wiser and Bolinger, 2010). This is fundamentally different from minimum generation related curtailment, which is the focus of this analysis and we assume that sufficient transmission capacity is added to avoid transmission related curtailment.

The minimum loading constraint and overall system flexibility largely depends on the mix of generation technologies in the system. A system dominated by gas or hydro units will likely have a higher level of flexibility than a system dominated by coal or nuclear generators. The flexibility of current systems can be difficult to assess, and is an area of active research (Denholm et al., 2010). In reality, the minimum load is not a hard constraint, but an economic issue based largely on the costs of thermal unit cycling, as well as the amount of operating reserves required, and the type of units providing those reserves. Instead of focusing on constraints in the current system, the focus of this analysis is to determine how flexible a system must be to accommodate up to 80% VG.

3. Simulation of high penetration cases using the REFlex model

To better understand the need for system flexibility, grid simulations were performed with the Renewable Energy Flexibility (REFflex) model (a modified version of the PVFlex model described in Denholm and Margolis, 2007a,b). REFlex is a reduced form dispatch model that compares VG supply with demand and calculates the fraction of load potentially met by VG considering flexibility constraints and curtailment. REFlex also can dispatch a variety of system flexibility options to determine the basic feasibility of matching RE supply with demand.

REFlex performs an hourly simulation and includes the electricity demand and the output from a variety of VG resources. The data are read into a series of Visual Basic for Applications (VBA) tools that compares VG output during each hour to the load that can be met by VG (equal to the load minus the minimum generation levels from conventional generators). If VG output exceeds this net system demand during any hour, then the excess VG output during this hour is curtailed (or may be placed into storage if available). As a reduced form dispatch model, REFlex does not commit individual thermal units based on generator operating constraints. Instead it evaluates the ability of an entire system to accommodate VG based on its aggregated system minimum generation level. This allows for a general understanding of the system flexibility needs of many different combination of VG, as opposed to a detailed technical and economic evaluation of any particular scenario.[5] The system minimum is an input to the model based on a fraction of system peak, representing the limits of both baseload generators and generators that must remain online to reliably meet the variability and uncertainty of the net load. This minimum load constraint can also be expressed more generally as the system's "flexibility factor," which is defined as the fraction below the annual peak to which conventional generators can cycle (Denholm and Margolis, 2007a,b). A 0% flexible system would be unable to cycle below annual peak load at all, while a 100% flexible system could cycle down to zero load. In these simulations, the amount of must-run generation was based on fixed levels to examine sensitivity to different levels of system flexibility.

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[5] Operational simulations (including stability and transmission analysis) and would be required to determine the actual feasibility of any individual scenario (Milligan et al., 2010). An evaluation of the substantial changes in electricity supply markets would also be needed to ensure the system flexibility required by these scenarios.

3.1. Load and utility system assumptions

This analysis simulated the Electric Reliability Council of Texas (ERCOT) system. Currently, the ERCOT system is electrically isolated from the rest of the United States, with a small import/export capacity of o 1 GW. As a result, virtually all electric demand in ERCOT must be met with generators located within the ERCOT territory. ERCOT is the smallest of the three US grids, serving about 20 million retail customers (85% of the state's load), with a peak demand in 2005 of about 60 GW, and a total annual demand in 2005 of 300 TWh (Saathoff et al., 2005). For comparison, ERCOT's total electric demand in 2005 was between the demand of Spain (245 TWh) and the United Kingdom (350 TWh) (EIA, 2010). ERCOT makes for an interesting case study, because of its isolation, and significant potential use of variable renewables. It has good solar and wind resources, with technical potential that exceeds current electricity demand, including sufficient direct normal irradiance to deploy concentrating solar power. However, ERCOT has limited access to baseload or dispatchable renewables such as hydro or geothermal. This combination may require ERCOT to depend more on variable renewables than other parts of the US, and acts as a "limiting case" to evaluate the impacts of VG on an isolated grid.

In framing our analysis, we made a number of assumptions about the utility system related to projected load growth, load profiles, transmission capacity, and transmission and distribution (T&D) losses. Below, we briefly discuss each of these assumptions.

Because this analysis focuses on the penetration of VG as a fraction of total energy, load growth on an energy basis will not impact our results, so it is not considered in this analysis. However, the shape of the daily and seasonal load profiles is critical for understanding how VG interacts with the system. ERCOT, like most of the US, is a summer peaking system, with seasonal demand patterns characterized in Fig. 1, and unlike many European systems which are winter peaking (ENTSO-E, 2008). While the load profile may change over decadal time scales due to changes in weather patterns, building technology, equipment, appliances, etc., these changes are hard to predict, so we assume the relationship between weather and electric demand remains constant in the base case. However we also evaluate the effect of load shifting as a sensitivity case.

We do not consider transmission constraints, and assume sufficient transmission capacity is constructed to access remote wind and concentrating solar power (CSP) resources in West Texas. We also did not consider the possible impacts of changes in T&D losses. Utility loads are measured at central locations so T&D losses then are considered part of the net load. Since wind and CSP generators may be further from loads than normal generators, it is likely that transmission losses for wind may be somewhat higher than average. Alternatively, much of the distributed solar PV generation will be deployed on rooftops or at load centers, reducing T&D losses. The net impact is difficult to assess so we assume that T&D loss rates for a VG dominated system are the same as for a conventional system.

Finally, we assume that ERCOT remains a single balancing authority, centrally dispatched to maximize the use of renewable energy, and electrically isolated. This is an overly restrictive assumption that in many ways presents a limiting case, as ERCOT already has some small interconnections with the other grids, and there are proposals to substantially increase these interconnections (TresAmigas, 2010). It is likely that a "cost-optimal" system would use transmission to exchange renewables with the Eastern and Western interconnects to share resources, reserves, and load.

3.2. RE data sources

Simulated wind data for 2005 and 2006 was obtained from AWS Truewinds (GE Energy, 2008). The data set includes a total of 76.8 GW of capacity, with an overall average capacity factor of 34.3%. A map of the wind resource areas, along with capacity and average capacity factor in each area is provided in Appendix A. Substantial new transmission capacity would be needed since much of Texas's best wind resources are in lightly populated areas in the west. Furthermore, several of the zones are actually outside the ERCOT territory. For additional discussion of the wind data, see GE Energy (2008).

For hourly PV production, solar data for 2005 and 2006 was derived from the updated National Solar Radiation Database (NSRDB) (NREL, 2007a,b; Wilcox and Marion, 2008). A total of 49 sites in ERCOT were used for the simulation, with a map and performance associated with each site provided in Appendix A. Solar insolation and temperature data was converted into hourly PV output using the Solar Advisor Model (SAM) (Gilman et al., 2008). We assume that PV will be distributed in a mix of rooftop and central systems (both fixed and 1-axis tracking) distributed in proportion to population. The distribution of orientation was based on an assumed mix of 50% central and 50% rooftop. Of the central PV, it was assumed that 25% is fixed (south facing , tilted at 251), with the remainder 1-axis tracking. The rooftop systems are assumed to be a mix of flat and fixed tilt systems with a variety of orientations based on Denholm and Margolis (2008b). It is not designed to be the optimal mix and should be viewed as being illustrative rather than prescriptive.

For CSP, SAM uses the direct normal irradiance (DNI) to calculate the hourly electrical output of a wet-cooled trough plant (Turchi, 2010). In the base case we assume no storage. A total of 145 sites in west Texas (where DNI exceeds 6.1 kWh/m^2/day and capacity factor exceeds 22%) were used. These sites, along with the solar resource are provided in Appendix A. As with wind, some of the best resources are outside of ERCOT, and we assume that dedicated transmission is constructed to access these resources.

4. Result—high VG scenarios without energy storage

4.1. Impacts of system flexibility

We first evaluate scenarios that examine the impact of system flexibility, or the ability of conventional generators to accommodate the variable nature of wind and solar generation. This initial scenario does not consider the role of load or supply shifting (via energy storage or other technologies), but does consider high levels of flexibility that will require supplying reserves with non-thermal generation such as demand response. The metrics evaluated include fraction of load met by VG, curtailment, and the corresponding increase in VG costs due to excessive VG curtailment.

Figs. 4–6 provide a framework for evaluating the feasibility and potential costs of these high-penetration scenarios. This initial simulation is a wind-only scenario, using the complete wind data set, and based on the system assumptions described in Section 3.1. Fig. 4 shows the total VG curtailment as a function of the fraction of the system's energy derived from usable (non-curtailed) VG. Three curves are shown for various flexibility factors – 80%, 90%, and 100%, which correspond to minimum generation points of 12, 6, and 0 GW.

The results in Fig. 4 follows many previous wind integration studies indicating fairly low levels of wind curtailment at penetrations up to 30%, assuming sufficient generator flexibility. Beyond these levels, the curtailment rate increases sharply, especially considering that a 100% flexible system is well beyond what is currently achievable given the dependence of the existing system on relatively inflexible baseload generators. Achieving 80% of the simulated system's electricity from wind generation only (and without storage) requires a system flexibility of close to 100%, and results in a curtailment rate of more than 43%. Due to

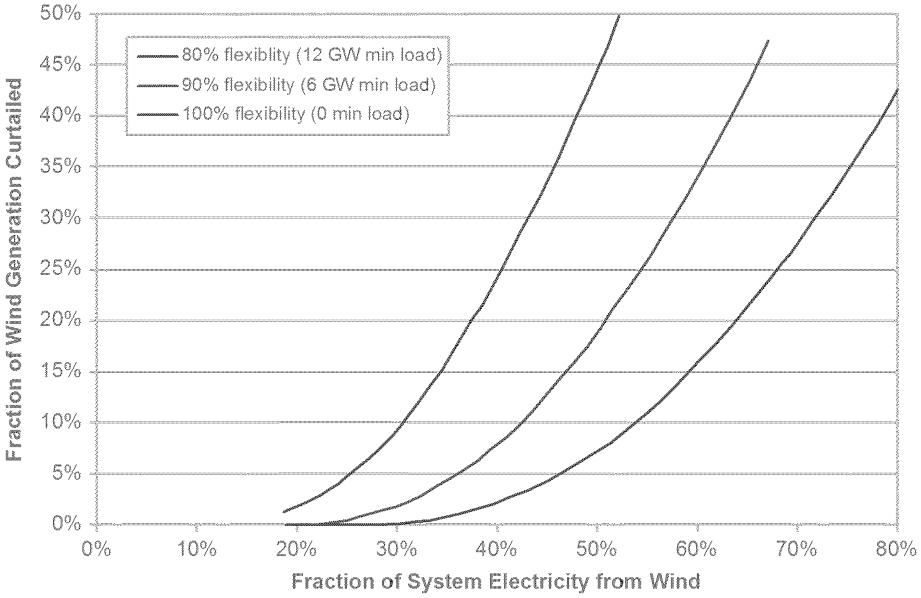

Fig. 4. Total curtailment as a function of usable wind energy penetration for different system flexibilities.

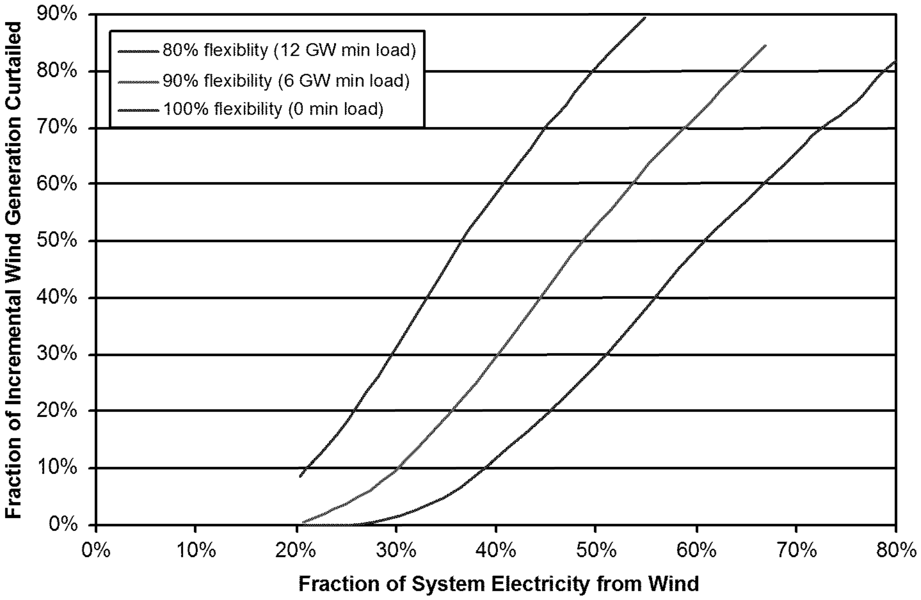

Fig. 5. Marginal curtailment as a function of usable wind energy penetration for different system flexibilities.

this high level of curtailment, the installed capacity of wind required to achieve 80% is about 140 GW, which exceeds the 77 GW of modeled wind output data. The actual wind resource in Texas is well over 1000 GW (NREL, 2007a), and this analysis assumes that the additional wind resource in ERCOT has the same temporal patterns as the modeled wind data set.

The curtailment rate at 80% penetration is probably beyond what is acceptable or cost-optimal. This concern can be emphasized by providing the marginal curtailment curves for the same data (and same flexibilities) in Fig. 5. In this curve, the curtailment rate is associated with each incremental unit of wind installed in the system. (As before, the energy penetration is defined as usable energy, subtracting out curtailed VG.) At 80% penetration, the incremental curtailment rate is over 80%, meaning that any additional wind will provide very little usable energy into the system.

At such high curtailment rates, this system is likely to be cost-prohibitive. As the curtailment rates increase, the effective capacity factor drops, resulting in substantially increased costs.[6] Fig. 6 illustrates how the marginal and average relative cost of electricity from wind changes as the level of wind penetration increases. The same data from Figs. 4 and 5 is translated into a relative cost of wind generation, measured as relative to a "base" cost of 1, i.e. the cost of electricity from wind without curtailment. The relative cost, equal to the inverse of (1-curtailment rate) is due only to curtailment and does not incorporate the cost of uncertainty or reserves typically classified as integration costs (Milligan and Kirby, 2009). There is a considerable difference between average and marginal costs, particularly at high penetration levels. For example, to achieve a 50% penetration level of wind in a 90% flexible system, the average cost of wind generation would be about 1.2 times the

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[6] The levelized cost of an energy system is proportional to the inverse of the capacity factor.

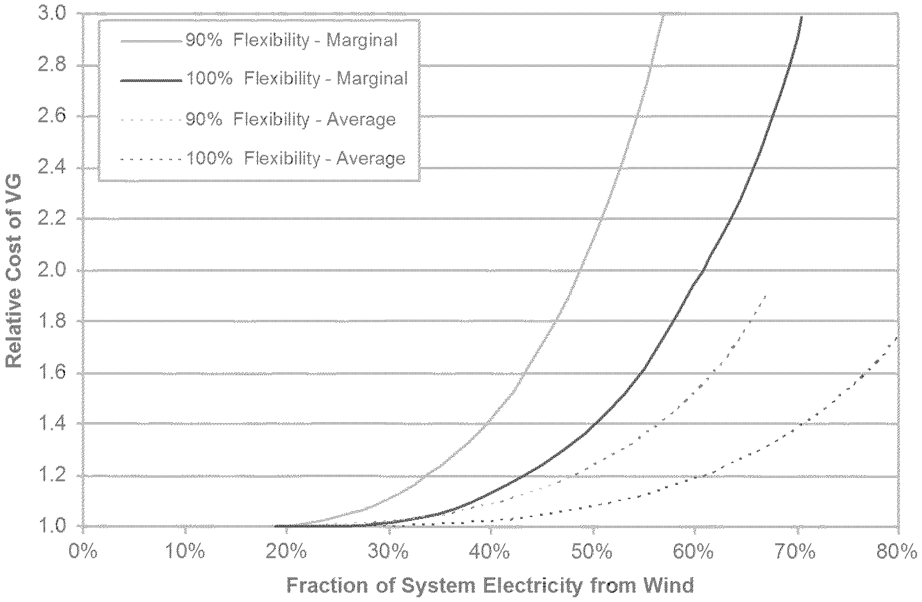

Fig. 6. Average and marginal relative cost of wind as a function of wind energy penetration due to increasing amounts of curtailment.

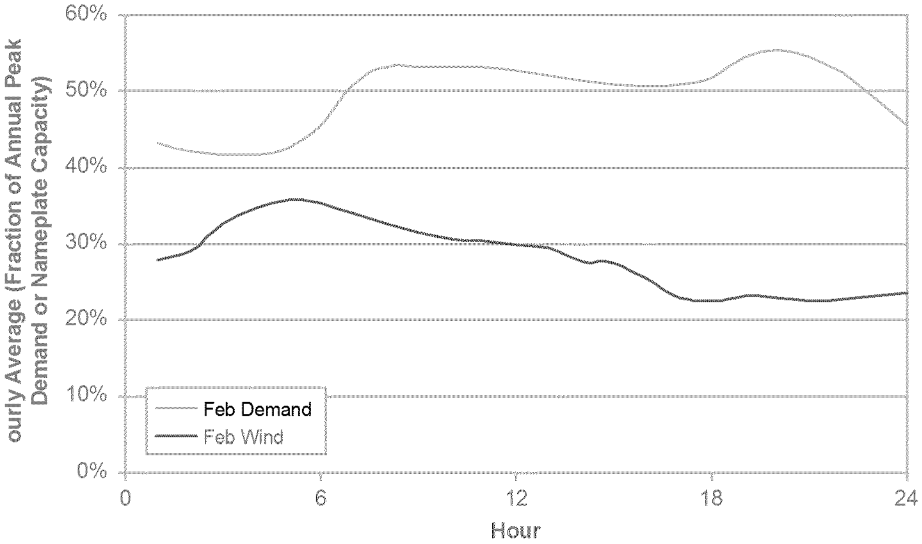

Fig. 7. Average daily wind output and electricity demand during February.

base cost. In other words, if the "base" cost of wind-generated electricity were 10 cents/kWh, the actual cost of every kWh of wind used in this system would be 12 cents/kWh in the 50% penetration/90% flexibility case. However, at the margin, the "last" unit of wind generation installed to meet the 50% penetration level would cost about two times the base cost, or 20 cents/kWh. At the 80% penetration level, the higher flexibility is required, and results in an average cost of wind at about 1.8 times the base cost, and the marginal cost for the last unit of wind installed to get to 80% would be over five times the base cost due to its high level of curtailment. (The effective capacity factor of this last unit of wind would be about 6%.) It is unclear whether the average or marginal costs will be the limiting factor, but this issue may be of some importance when evaluating the likelihood of high VG penetration—especially considering market evaluation and rules for "allocation" of curtailment.

The sharply increasing curtailment rates (and corresponding costs) are due to the limited correlation of wind and load. Once the threshold of curtailment is met, an increasing fraction of additional wind occurs during those periods of curtailment. This is illustrated in Figs. 7 and 8 which show the seasonal and daily patterns of both wind and load. The figures show the average wind output (as a fraction of nameplate capacity) and the average demand (as a fraction of peak demand). The figures indicate that wind and demand tend to be anti-correlated, with wind peaking in the morning and demand peaking in the afternoon. These patterns of load/wind correlation are similar to those in much of the US, but not necessarily similar to those in Europe or locations (GE Energy, 2010; Holttinen et al., 2009). As a result, it is unclear how the results of this study can be more generally applied. These patterns also suggest a mix of wind and solar resources could improve the coincidence of VG and load due to solar's greater production during the middle of the day.

4.2. Impacts of wind/solar resource mix

Fig. 9 shows how the curtailment rates change with the addition of solar in a 100% flexibility (0 minimum load) scenario. The mix is shown based on relative fraction of solar and wind generation. As a

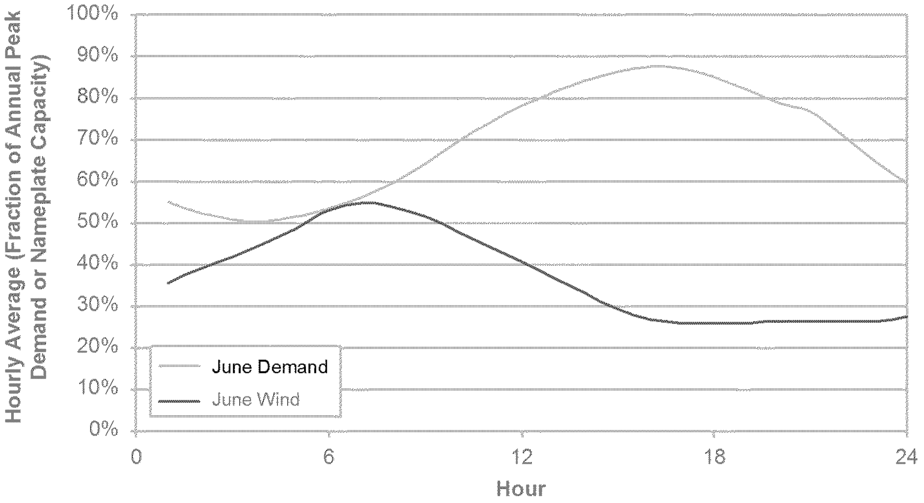

Fig. 8. Average daily wind output and electricity demand during June.

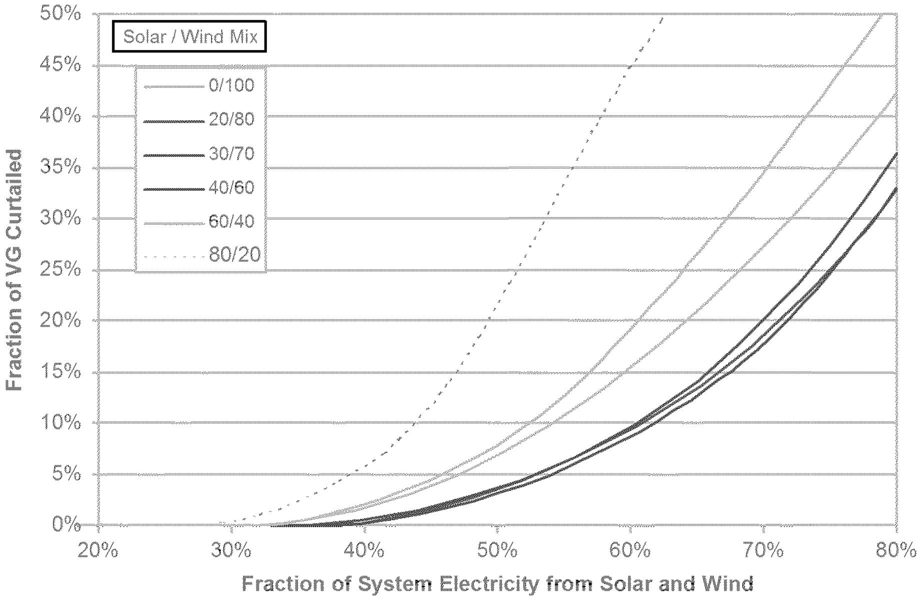

Fig. 9. Total curtailment as a function of VG energy penetration for different solar/wind mixes (assuming a 100% flexible system).

result, the point on the curve labeled "40/60" where VG is providing 50% means solar is providing 20% of the total demand (40% of 50%) and wind is providing 30% of demand (60% of 50%). As with wind, the regional mix of solar remains the same (as more solar is introduced, the distribution of solar locations remain the same, but there is just more of it at each location). For reference, the curve labeled "0/100" (meaning only wind and no solar) is the same as the 100% flexibility curve in Fig. 4. As solar is added curtailment rates drop, since the wind/solar mix is better correlated with normal demand, and less generation from this new mix occurs during periods of low demand. The minimum level of curtailment occurs in the 30% solar case (in which solar is supplying 30% of the RE generation with wind supplying the other 70%). Beyond 30%, the curtailment rate then increases rapidly, since solar exhibits far less spatial diversity than wind (particularly over hourly time scales and within the geographical constraints of this analysis), with output concentrated in less than half of the hours. This issue is discussed in length in Denholm and Margolis, 2007a,b). As noted before, this mix is designed to minimize curtailment, as opposed to minimize system costs, since it is difficult to predict potential cost reductions in PV and CSP over the time scales needed to achieve this level of penetration. While the total curtailment rate has dropped, at 80% penetration the marginal curtailment rate remains very high, exceeding 80%, meaning the last unit of VG put into the system will cost more than five times the base cost.

Even with the "optimum" mix of wind and solar and the completely flexible system assumed in Fig. 9, there are still fundamental limits to the correlation of supply and demand, primarily due to the limited production of wind and PV in the late afternoon and early evening when demand peaks. Further reduction in VG curtailment at high VG requires an additional source of flexibility is required, namely the ability to increase the coincidence of VG supply with demand.

5. High VG scenarios with energy storage and load shifting

The previous section shows that high levels of generation flexibility are necessary to achieve extremely high levels of VG,

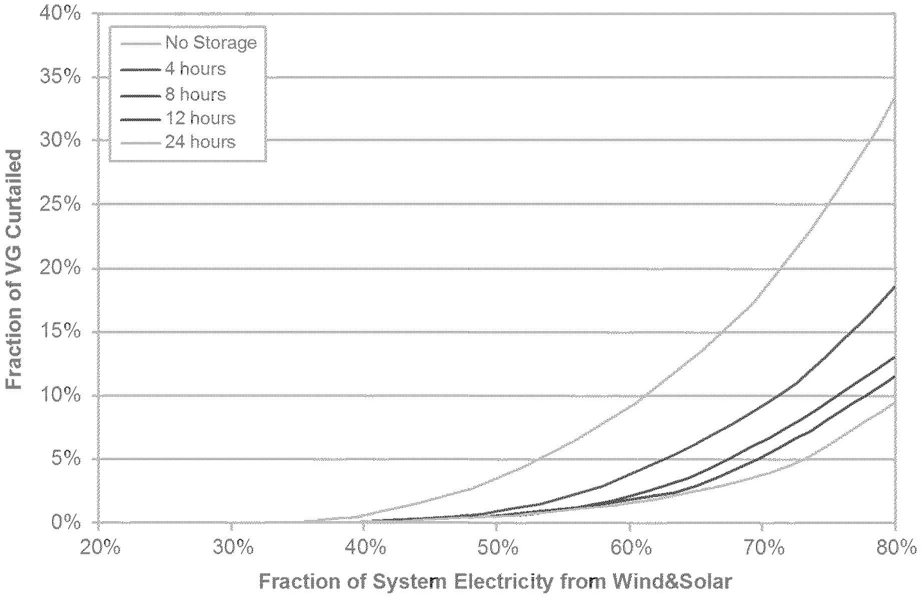

Fig. 10. Total curtailment as a function of VG energy penetration for different amounts of energy storage. (Assumes 30/70 solar/wind mix and a 100% flexible system. Each hour of storage represents one of average system demand.)

but not sufficient due to limited supply/demand coincidence and resulting curtailment.[7]

While there are a number of approaches to increasing supply/demand coincidence, our focus was estimating the amount of energy that must be shifted to increase use of VG and decrease curtailment. Because it will be some time until very high penetrations of VG are achieved, and there are many storage and load shifting technologies available or under development, we did not prescribe the specific type of load shifting or storage technology used. As a result, we assumed load can be shifted with devices with round-trip efficiencies of 60%, 80% and 100%. The 60% and 80% efficiencies represent the range of many commercially available storage technologies such as batteries and pumped hydro storage (EPRI, 2003). The 100% efficient case represents end-use load shifting, or approximates the extremely high round-trip efficiencies of thermal storage in buildings or in CSP plants. There are important caveats about the use of both load shifting and thermal storage. Thermal storage is coupled to a single application, whether on the supply side in CSP plants, or on the demand side, such as with cold storage. There are also obviously limits to how much load can be shifted. However, it is very important to consider thermal storage approaches due to both their higher round-trip efficiencies and potentially lower capital cost. More comprehensive analysis as to the technical and economic potential of load shifting must be performed, as well as detailed simulations of the load shifting possibilities of thermal storage. However, this analysis provides some insight into the amount of load shifting and storage required.

Fig. 10 shows the impact of adding energy storage with an 80% round-trip efficiency. The mix of solar and wind is 30%/70% and the system flexibility is 100%. The no storage curve then is identical to the 30/70 curve in Fig. 9, or the mix with the lowest curtailment rate. In this figure the amount of storage in the system is characterized by hours of average system demand. In this case, the average hourly demand is 34.4 GW, so 1 h of storage represents 34.4 GWh. Storage devices are characterized by both the energy capacity and power capacity, with the relationship given by the energy to power ratio, or the number of hours of storage capacity at full discharge. For example a pumped hydro plant may be rated at 1000 MW, with 12 h of storage capacity, corresponding to an energy capacity of 12 GWh. We assumed that the typical device used for bulk storage would have an energy to power ratio of 12, so each hour of system capacity (34.4 GWh) actually corresponds to a 2.9 GW device with 12 h of storage capacity.

Fig. 10 shows that the use of storage dramatically reduces the curtailment needed to achieve very high penetrations of VG. Note that curtailment includes losses in the storage device (a unit of energy placed into storage will have a curtailment rate of 20% due to the 80% round-trip efficiency).

Fig. 10 shows that a relatively small amount of storage can be used to shift the daily lack of coincidence, as illustrated previously. However there are substantial diminishing returns for greater amount of storage. The first 4 h of storage decreases curtailment by 43% from about 33% to about 19% at 80% penetration, while moving from 8 to 12 h of storage only decreases curtailment from about 13% to 12%. This amount of storage (12 h of average demand) corresponds to about 34 GW of power capacity and 414 GWh of energy capacity, and exceeds the total capacity of electricity storage currently installed in the US of about 21 GW, nearly all of which is pumped hydro (Denholm et al., 2010). There is currently no large-scale storage (electricity or CSP/thermal) deployed in ERCOT, although there are proposals for new pumped hydro and compressed air projects in Texas (FERC, 2010; Succar and Williams, 2008). Reducing the curtailment rate to less than 10% would require storage capacity of nearly 1 day of average demand, and the marginal curtailment rate with this amount of storage still exceeds 40%. Given the high costs of many current storage technologies, this emphasizes the need to explore all options for increasing flexibility including increasing system interconnections, demand response, load shifting, electrified transportation, thermal storage, and advanced, lower-cost electricity storage technologies.

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[7] An additional challenge is the significant ramping requirements of the system in a high VG scenario. For example in the base scenario (no VG) the maximum ramp rate requirement of the conventional generation fleet is 4.8 GW/h. In the case where wind and solar provide 50% of the system's energy, the net load ramp rate (load minus contribution from wind and solar) exceeds 10 GW/h during 49 occasions during the year. This provides another motivation for sharing wind and load resources over large areas, which act to reduce the ramp rates of the net load (NERC, 2010)).

The limitations of larger amounts of storage are due to two factors. First, reduction in curtailment is fundamentally limited by losses in the storage process. Fig. 11 shows the effect on total curtailment as a function of the three storage efficiencies. The no storage case is the same as the no storage case in Fig. 10, with the three storage cases assuming 12 h of storage (34 GW/414 GWh). Moving from an 80% to a 100% efficient device decreases curtailment at 80% penetration from 11% to 10% with 12 h of storage/load shifting. This high efficiency represents the potential use of thermal storage, or load shifting and demand response, which could be cost-effective alternatives (or complements) to electricity storage technologies.

The second and more important factor decreasing the benefit of increasing amounts of storage is limited seasonal correlation of the combined VG mix and demand. Neither wind nor solar are perfectly correlated with load on an hourly or daily basis, but this can be addressed with short-term (a few hours) storage or load shifting. However, seasonal mis-matches are more difficult to address. Fig. 12 shows the average monthly output (normalized to peak output) for the load, wind and solar in ERCOT. Wind has the greatest non-correlation with load – it peaks in March and April, and again in November – three of the lowest demand months. Fig. 12 shows that even if all of the short-term coincidence issues are addressed, it is difficult to meet a very large fraction of the demand without the ability to move energy over longer time scales. Solar is better correlated but also tends to produce large amounts of energy in the spring during times of relatively low demand. It should be noted that as the amount of storage increases the "optimal" mix of wind and solar (based solely on curtailment rate) changes—at 12 h of storage the optimal mix moves from 30%/70% solar/wind closer to

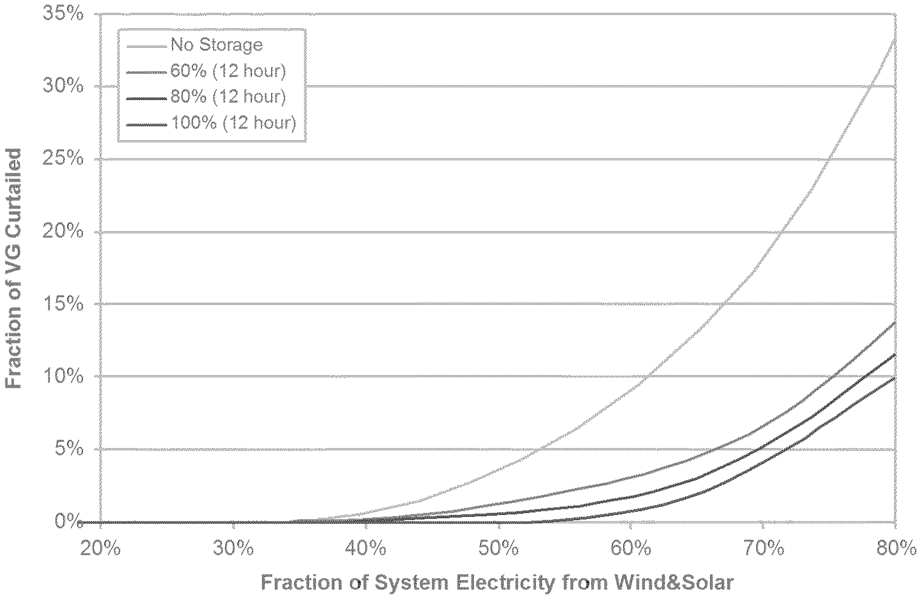

Fig. 11. Total curtailment as a function of VG energy penetration for different amounts of storage efficiencies. (Assumes 30/70 solar/wind mix, 12 hours of storage and a 100% flexible system.)

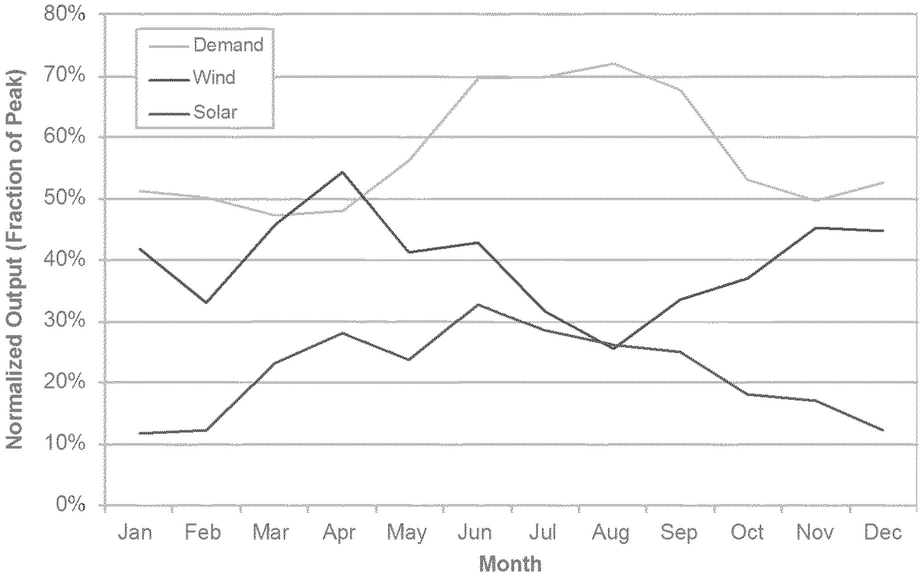

Fig. 12. Average monthly wind and solar output and electricity demand.

50%/50%. However, the total curtailment rate drops only by a few percentage points. Regardless of the mix of solar and wind, the supply of VG saturates the demand for electricity in the spring.

This seasonal mismatch would need to be addressed by either extremely long-term storage, such as air compression in very large reservoirs (Cavallo and Keck, 1995) or through new electrification applications that are flexible over various time scales, perhaps including fuel production. However, as with conventional storage, these approaches need to be placed in the context of the assumptions of this analysis. It may be much cheaper to connect the ERCOT grid to its neighbors to take advantage of a more diverse set of both VG and dispatchable renewables.

6. Conclusions

Our evaluation of ERCOT evaluates a limiting case including an isolated grid depending largely on variable renewables. This ignores dispatchable renewables such as hydro, geothermal, and biomass which would reduce the dependence on VG to achieve high levels of renewable electricity generation. This also ignores the opportunities for transmission interconnection between ERCOT and the remaining US to share resources and load, a key source of low-cost system flexibility.

Given these caveats, in an isolated system such as ERCOT achieving 80% electricity from VG is greatly dependent on increased generation flexibility, virtually eliminating minimum generation constraints imposed both by "must-run" baseload generators, and other thermal units kept on line to provide operating reserves. This also means replacing conventional spinning reserves and regulation reserves with a combination of demand response, use of curtailed VG, and other enabling technologies such as energy storage. At 80% generation from variable renewables, the remaining 20% of generation would need to be able to start and ramp extremely rapidly to respond to the highly variable and uncertain residual load.

Even with a completely flexible system, achieving 80% from VG sources in the evaluated system requires enabling technologies to address the fundamental mismatch of supply and demand. Avoiding excessive curtailment will likely require a variety of enabling technologies including load shifting, thermal storage, or electricity storage. A system capable of storing or moving 4 h of average system load can reduce curtailment to below 20% with the analyzed mix of wind and solar at 80% penetration. However the seasonal mismatch of VG resources and demand makes reduced curtailment more difficult to address using "conventional" storage technologies without very long duration (well over 24 h) storage capacities.

While the lack of power exchanges between ERCOT and the other interconnects limits definitive conclusions, this analysis reinforces and extends conclusions of previous wind and solar integration studies both in the US and worldwide. These include the critical role of deploying flexible generation on multiple time scales. A variable generation-based grid of the future must include generation that can start, stop, and ramp rapidly. It must also be able to quickly deploy reserves that may be better served by responsive load. Methods of shifting demand will become increasingly valuable, whether by markets and price responsiveness, or via new end use technologies such as thermal storage in buildings. Finally, this analysis suggests that energy storage of all types including both electricity storage and thermal storage can provide a critical role in VG integration particularly at penetrations beyond 50%. Ultimately, additional analysis will be needed to understand the grid-level changes required for the many combinations of VG, dispatchable renewables, and non-renewable sources of low-carbon electricity that may be deployed both in the US and worldwide.

Appendix A. Wind and solar resource data

For a map of the wind resource areas, along with capacity and average capacity factor in each area, see Figs. A1–A3 and Tables A1 and A2.

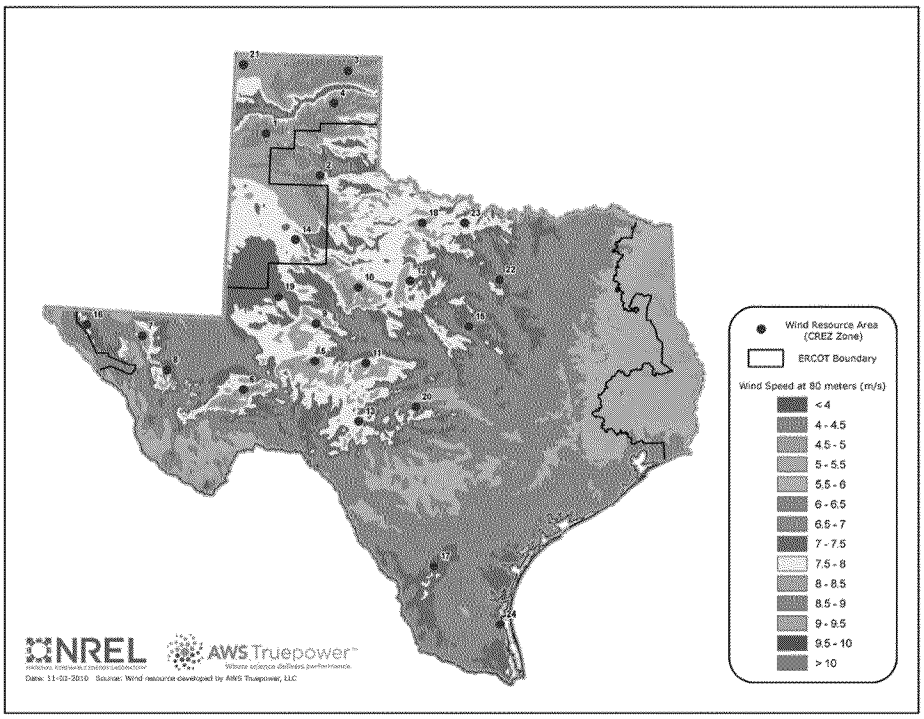

Fig. A1. Map of ERCOT territory and wind resource sites used in the analysis.

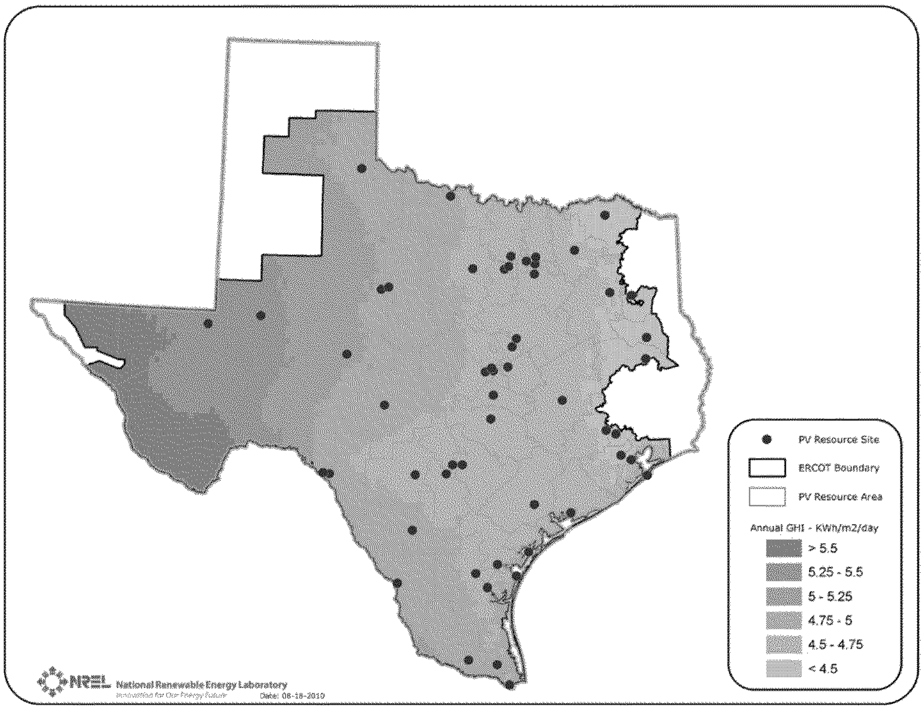

Fig. A2. Map of ERCOT territory and solar PV resource sites used in the analysis. Areas were assigned to each resource site based on proximity of census block groups.

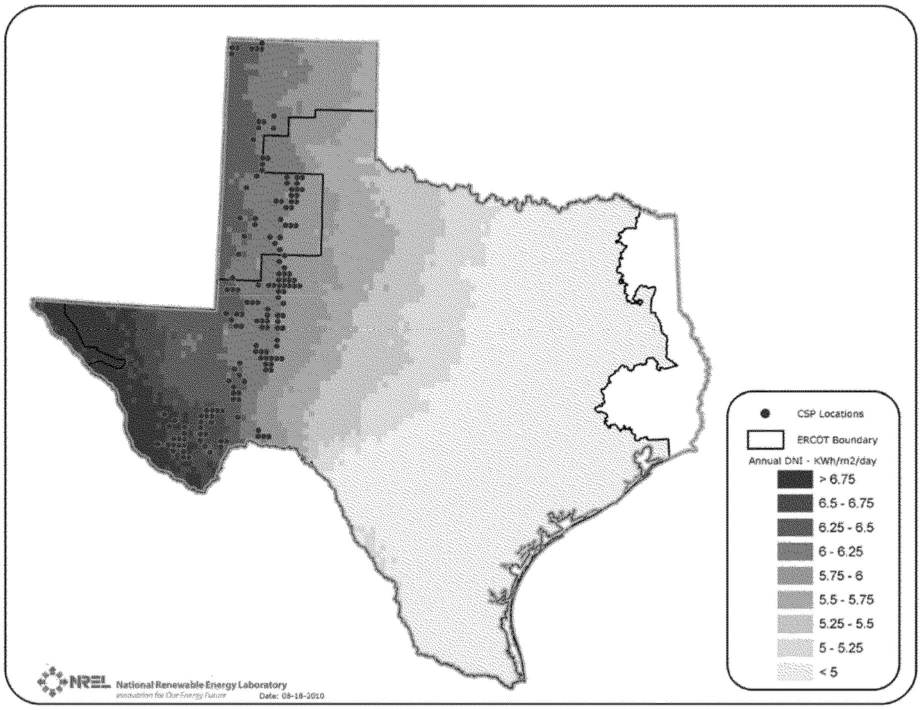

Fig. A3. Map of ERCOT territory and CSP resource sites used in the analysis.

Table A1
Wind resource areas and characteristics (see GE 2008 for additional information).

Crez zone	Total modeled capacity	Average capacity factor
1	3927	40.5
2	3971.4	41.3
3	3997.6	43.5
4	3947.4	41.8
5	3966.2	39.5
6	3962.9	40.5
7	1728.5	36.6
8	1741.6	35.7
9	3928.3	37.7
10	3970.1	38.2
11	3978.3	34.0
12	3865.3	32.9
13	2861	30.6
14	3974.5	36.0
15	2712.9	31.1
16	303.4	31.2
17	3965.1	32.0
18	3895.5	31.5
19	3749	30.1
20	2196.7	30.3
21	1279.4	38.3
22	401.7	30.0
23	3540.1	30.2
24	2254.1	34.7
25	2707.6	33.8

Table A2
Solar PV sites and capacity factor. Note capacity factor calculation uses the Solar Advisor Model (SAM) which includes a temperature-based parameterization of PV efficiency and estimates of DC–AC conversion losses.

USAF	Name	Annual production (kWh/kW)		Capacity factor	
		Fixed 251S	1-Axis tracking	Fixed 251S (%)	1-Axis tracking (%)
690190	ABILENE DYESS AFB	1572	2032	17.9	23.2
722410	PORT ARTHUR JEFFERSON COUNTY	1437	1824	16.4	20.8
722420	GALVESTON/SCHOLES	1489	1874	17.0	21.4
722429	HOUSTON/D.W. HOOKS	1427	1810	16.3	20.7
722430	HOUSTON BUSH INTERCONTINENTAL	1419	1797	16.2	20.5
722435	HOUSTON WILLIAM P HOBBY AP	1433	1817	16.4	20.7
722436	HOUSTON ELLINGTON AFB [CLEAR LAKE – UT]	1470	1887	16.8	21.5
722445	COLLEGE STATION EASTERWOOD FL	1439	1820	16.4	20.8
722446	LUFKIN ANGELINA CO	1415	1805	16.2	20.6
722448	TYLER/POUNDS FLD	1448	1849	16.5	21.1
722470	LONGVIEW GREGG COUNTY AP [OVERTON – UT]	1471	1914	16.8	21.8
722499	NACOGDOCHES (AWOS)	1421	1807	16.2	20.6
722500	BROWNSVILLE S PADRE ISL INTL	1397	1761	15.9	20.1
722505	HARLINGEN RIO GRANDE VALLEY I	1411	1788	16.1	20.4
722506	MCALLEN MILLER INTL AP [EDINBURG – UT]	1454	1863	16.6	21.3
722510	CORPUS CHRISTI INTL ARPT [UT]	1453	1869	16.6	21.3
722515	CORPUS CHRISTI NAS	1470	1853	16.8	21.2
722516	KINGSVILLE	1423	1808	16.2	20.6
722517	ALICE INTL AP	1413	1793	16.1	20.5
722520	LAREDO INTL AP [UT]	1450	1861	16.5	21.2
722524	ROCKPORT/ARANSAS CO	1484	1879	16.9	21.5
722526	COTULLA FAA AP	1404	1788	16.0	20.4
722530	SAN ANTONIO INTL AP	1416	1790	16.2	20.4
722533	HONDO MUNICIPAL AP	1435	1821	16.4	20.8
722535	SAN ANTONIO KELLY FIELD AFB	1419	1792	16.2	20.5
722536	RANDOLPH AFB	1424	1801	16.3	20.6
722540	AUSTIN MUELLER MUNICIPAL AP [UT]	1448	1850	16.5	21.1
722547	GEORGETOWN (AWOS)	1437	1831	16.4	20.9
722550	VICTORIA REGIONAL AP	1431	1814	16.3	20.7
722555	PALACIOS MUNICIPAL AP	1472	1859	16.8	21.2
722560	WACO REGIONAL AP	1483	1892	16.9	21.6
722563	MC GREGOR (AWOS)	1487	1893	17.0	21.6
722570	FORT HOOD	1474	1878	16.8	21.4
722575	KILLEEN MUNI (AWOS)	1482	1888	16.9	21.6
722576	ROBERT GRAY AAF	1472	1870	16.8	21.3
722577	DRAUGHON MILLER CEN	1450	1835	16.6	20.9
722583	DALLAS LOVE FIELD	1475	1880	16.8	21.5
722587	COX FLD	1494	1910	17.1	21.8
722588	GREENVILLE/MAJORS	1464	1869	16.7	21.3

Table A2 (continued)

USAF	Name	Annual production (kWh/kW)		Capacity factor	
		Fixed 251S	1-Axis tracking	Fixed 251S (%)	1-Axis tracking (%)
722590	DALLAS-FORT WORTH INTL AP	1491	1901	17.0	21.7
722594	FORT WORTH ALLIANCE	1510	1940	17.2	22.2
722595	FORT WORTH NAS	1502	1926	17.1	22.0
722596	FORT WORTH MEACHAM	1509	1940	17.2	22.1
722597	MINERAL WELLS MUNICIPAL AP	1519	1940	17.3	22.2
722598	DALLAS/ADDISON ARPT	1489	1900	17.0	21.7
722599	DALLAS/REDBIRD ARPT	1486	1899	17.0	21.7
722610	DEL RIO [UT]	1450	1834	16.5	20.9
722615	DEL RIO LAUGHLIN AFB	1444	1844	16.5	21.1
722630	SAN ANGELO MATHIS FIELD	1581	2028	18.0	23.2
722636	DALHART MUNICIPAL AP	1689	2204	19.3	25.2
722650	MIDLAND INTERNATIONAL AP	1658	2151	18.9	24.6
722656	WINK WINKLER COUNTY AP	1681	2183	19.2	24.9
722660	ABILENE REGIONAL AP [UT]	1594	2081	18.2	23.8
722670	LUBBOCK INTERNATIONAL AP	1669	2165	19.1	24.7
722700	EL PASO INTERNATIONAL AP [UT]	1781	2296	20.3	26.2
723510	WICHITA FALLS MUNICIPAL ARPT	1539	1977	17.6	22.6
723604	CHILDRESS MUNICIPAL AP	1602	2067	18.3	23.6
723630	AMARILLO INTERNATIONAL AP [CANYON – UT]	1667	2165	19.0	24.7
747400	JUNCTION KIMBLE COUNTY AP	1508	1933	17.2	22.1

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ATTACHMENT 8

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[-75%75A5.,*12%5.57@1%+,-70@5%H0+%0AH45I5M%75A-@.4,4-.%0+%0%R-3.M0,4-.0*%5*5C5.,%-R%,H5%4+C07%\74M%[&]2%0.M%,H5% ,5AH.4A0*%A-CC3.4,1%+S508+%-R%5.57@1%+,-70@5%0+%0%851%5.0N*4.@%75+-37A5%-%R0A4*4,0,5%,H5%70.+4,4-.%0?01%R7-C%0% R-++4*%R35*%M-C4.0,5M%@5.570,4-.%R*55,%-%.5%,H0,%4+%A*50.57%C-75%75*40.%-.%75. * * * * * * * * [2] * * * * * * * * * * * * * * * * * * 0AA5*570,5%,H5%5*5A,74R4A0,4-.%-R%,H5%,70.+S-7,0,4-.%+5A,-7%

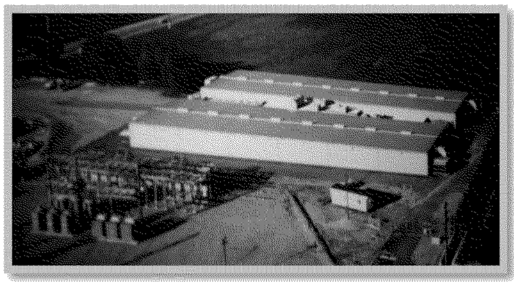
P-%H5*S%4*3+,70,5%,H5%A-+,%5RR5A,4I5.5++%-R%5.57@1%+,-70@5%0+%0.%0*,57.0,4I5%,-%.0,370*%@0+%R75M%S508+2%?5% A-CS075M%,H5%A-+,%-R%0%8*-?0,XH-37%8/H%-R%5*5A,74A4,1%@5.570,5M%-.XS508%N1%0%@0+%R75M%S5085722%?4,H%,H5%A-+,% -R%0%8/H%-R%5*5A,74A4,1%S7-I4M5M%-.XS508%N1%0.%5.57@1%+,-70@5%+1+,5C%0-7%4C S*4A4,12%,H4+%A-CS074+-.%+5*5A,5M%0% A-CC57A40**1%0I04*0N*5%5.57@1%+,-70@5%,5AH.-*-@1%%50M%0A4M%N0,,5745+%0*.M3+5M%,H5%A-+,%0.M%+S5A4R4A0,4-.+% +4C4*07%-%,H5%07@5%50M%0A4M%5.57@1%+,-70@5%S508.@%R0A4*4,1%+H-?.%N5*-?%]-A0,5M%4.%!H4.-2%!0*4R-7.402%,H4+%')% C5@0?0,%T[/U2%H-37%M370,4-.%* *-0M%R7-C%'9>>%,H7-3@H%'99=<[3]%

!"#$%&'()*$+%#'<#=."*1*%3#8'<*0+&'-+"'>#134#$'?",:#+;'!1#=)$3=3)&'+)'+@*A#$'-*8)').+"'7+8,93$#0':#+;#$8'

7+8,93$#0'<6$B3"#':#+;#$':1+")'

%

!"#$%&'()*$+%#':#+;#$'(6B8)3)6)3*"'



%

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[1] %F3CS5M%H1M7-%5.57@1%+,-70@52%?H4AH%H0+%N55.%4.%?4M5%3+5%R-7%C0.1%1507+24%0.-,H57%R-7C%-R%C5AH0.4A0*%2-7%84.5,4A%5.57@1%+,-70@5

[&] %4,*%0101%-R%,H5%".57@1%D.M5S5.M5.A5%0.M%#5A374,1%$A,%-R%&))%M5+A74N5M%,H5%4#C07%\74M%0+%4.A*3M4.@%* * * * * * * * * * * *0,4*.%-R%0M%*0.A5M%5*5A,74A4,1%* * * * * * * * * * * * +,-70@5%0.M%5S508X+H0I4.@%,5AH.-*-@45+24.A*3M4.@%S*3@X4.%5*5A,74A%0.M%H1N74M%5*5A,74A%I5H4A*5+2%0.M%,H57C0*%* *

[3] %".57@1%+,-70@5%S57R-7C0.A5%+S5A4R4A0,4-.+%N0+5M%-.%A-CC57A40**1%I5*S*-15M%50M%0A4M%@74M%+,-70@5%S7-^5A,+24.A*3M4.@%,H5%'F_D*R3*.M5M%@74M%5I5*%5.57@1% +,-70@5%M5C-.+,70,4-.%S7-^5A,%4.%!H4.-2%!0*4R-7.40

%'F_D%!H4.-%#,3M1%P_X')';>;2%'"#$%&'())*+,&-$*+.,&/)%+(.*&0%1*&02($)&-$.#$**+%4%6*7%+8%6*9%+)%'J5A5CN57%'99&U

!"#$%*%&'()%$*+,-.%/012#34,5%&')%6578*512!$%9:;)%%*%(')<==(<;>'%*%?? ?<+,-70@5040.A5<-7@%**

$'&B%#1+,5C+%*%$D!E"0+%F5.%*%$*,04G0.-%*%650A-.%F-?57%*%!H5I7-.%'.57@1%#-*3,4-.+%*%J5510%'.57@1%

".57#1+%*%".57K03*%*%'L4V5%*%J5N5.H0C%'.57@1%*%D*34M4A%'.57@1%*%A5%'.57@1%*%D.57,40%'.57@1%

F-?57@5,4A+%*%F73M5.%'.57@1%*%FKP%#-*07%*%#0C+3.@%#JD%*%#3.,5AH%*%#3+,04.0O%*%Q,75C5F-?57%

FO@5%%-R%>

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!"#$%&'()*$+%#','+'-.#+/#$'+"0'-1#+"#$'21)#$"+)34#')*'
5+)6$+1'7+8,93$#0':#+;#$8'

$++3 C S,4-.+%R-7%,H5%@0+TR475M%S50857%* * * * * * * * * * * * * * * * *!*" # $%&%*'()*+!*",*+*-+!%(-*&/*(%+! */'8%+ * * * * * * * * * *
*0'%'("/+1.*2'&(2('3+4*/*8%'("/+5*26/"."7(*,%C -M5*%P -%A0*A3*0,5%,H5%A-+,%S57%8 / H%-R%5*5A,74A4,1%M4+AH07@5M%N1%0.%*
5.57@1%+,-70@5%+1+,5 C2%,H5%+0 C5%&) T1507%S7-U5A,%4C5%H-74V-.%0.M%(W%A0S0A4,1%R0A,-7%? 575%3+5M%65*-?%4+%0%
M5,04*5M%-I57I45 ?%-R%,H5%0.0*1+4+%C5,H-M-*-@1%

%

7+8,93$#0':#+;#$':1+")[(]			
7#"#$+1'2886>/)3*"8'			
?#@."*1*%&A'	#4C S*5%1A*5%-CN3+,4-.%P37N4.5%		
:1+")'(3B#'	:9<9 Y /%		
!CG@#"@&'	B;W%Z92&=%6,3E8 / H%[50%\0,5%		
DE"#$8.3/'	F^_%^?.5ME04.0.A5M%		
:$*F#@)'G3C#'	&)%1507+%		
-+/+@3)&'9+@)*$'	(W%		
:1+")H?IJ'G*88#8'	=W%Z!5.,70%4V5M%F*0.,%		
-*8)8'	**2886>/)3*"8'**	**G-D7' KIMN O.P'**	**G-D7' KIM;O,8$P'**
93Q#0'DIN'	a&:E8 / E17%	a=9%	a&9%
-*$/R'?+Q#8'	)W%	a)%	a)%
S"86$+"@#'	)<=W%-R%d $F"Q%	a&B%	a')%
:$*/#$)&'?+Q'	'<'W%-R%d $F"Q%	a&9%	a'&%
5+)6$+1'7+8' 96#1'	a='EY / H%	a')%	a:%
T+$3+<1#'DIN'	a)<):E8 / H%	a(%	a&%
(6<)*)+1'	%	a&&,%	a9B%

!"#$%&'()*$+%#':#+;#$'(6<8)3)6)3*"="'			
7#"#$+1'2886>/)3*"8'			
?#@."*1*%&A'	`50M$A4M%60,,57%		
:1+")'(3B#'	:9<9 Y /%Z:H%B70,4-.%		
!CG@#"@&'	>:W%Z$!%-%$!%\-3.M,74S%		
DE"#$8.3/'	F^_%^?.5ME04.0.A5M%		
:$*F#@)'G3C#'	&)%1507+%		
-+/+@3)&'9+@)*$'	(W%		
:1+")H?IJ'G*88#8'	=W%Z!5.,70%4V5M%F*0.,%		
-*8)8'	**2886>/)3*"8'**	**G-D7' KIMN O.P'**	**G-D7' KIM;O,8$P'**
93Q#0'DIN'	a=E8 / E17%	a',%	a,%
-*$/R'?+Q#8'	)W%	a)%	a)%
S"86$+"@#'	)<=W%-R%d $F"Q%	a&&%	a9%
:$*/#$)&'?+Q'	'<'W%-R%d $F"Q%	a&<%	a'&%
DCC,:#+;'7$30' -.+$%3"%	a&:EY / H%	a:>%	a&)%
T+$3+<1#'DIN'	a)<):E8 / H%	a(%	a&%
(6<)*)+1'	%	a'&%	a()%

%

-*8)8'	2886>/)3*"8'	G-D7' KIMN O.P'	G-D7' KIM;O,8$P'
S"8)+11#0'-*8)'	a'2B9:E8 /%	a&=(%	a')9%
7$+"0'?*)+1'	%	a:98%	a&)B%

%

-*8)8'	2886>/)3*"8'	G-D7' KIMN O.P'	G-D7' KIM;O,8$P'
S"8)+11#0'-*8)'	a'2B('E8 / % ZaBB>E8 / H%	a&(=%	a')(%
7$+"0'?*)+1'	%	aB;,%	a'((%

!"#"$&"'()*+,(*-(."/"01,%*/(-*0(2/"034(5,*013"(%+(!"++(671/(1(5%8 9$"()4:$'(.1+;<%0"'(="1>"0%

%

!"#$%&'()*$+%#'U+8').#'2<3B)&')*'J#1B4#$'N*$#').+"':#+;#$'(6<8)3)6)3*"'T+16#')*').#'7$30'

D.%0MM4,4-.%,-%A-+,%+0I4.@%R-7%5*5A,74A4,1%A-.+3 C57+2%5.57@1%+,-70@5%S7-I4M5+%C3*,4S*5%I0*35%+,750C+%0N-I5%0.M% N51-.M%S50857%+3N+,4,3,4-.2%C084.@%,H5%5A-.-C4A%A0+5%R-7%5.57@1%+,-70@5%5I5.%+,7-.@57%O-7%5LOCS*52%N1%,H54%.0,3752%@0+TR475M%S50857%S*0.,+%A0..-,%N5%5A-..-C4A0**1%4V5M%N5*-?%()%Y /%0.M%,H575R-75%075%.-%50+4*1%4.+,0**5M% 4.%0%M4+,74N3,5M%R--,S74.,%'.57@1%+,-70@5%+1+,5C+%M-%.-%H0I5%,H4+%4C4,0,4-.2%-S5.4.@%3S%,H5%S-,5.,40*%R-7%C0.1% ,5AH.4A0*%0.M%5A-..-C4A0*%N5.5R4,+%0I04*0N*5%,-%M4+,74N3,5M%5.57@1%75+-37A5+%+3AH%0+%75M3A,4-.%-R%,70.+C4++4-.% 0.M%M4+,74N3,4-.%*-++5+%$MM4,4-.0*%N5.5R4,+%4.A*3M5%5*5A,74A%5.57@1%,4C5T+H4R,2%I-*,0@5%+3SS-7,2%5*5A,74A%+3SS*1% 75+5715%A0S0A4,12%,70.+C4++4-.%A-.@5+,4-.%75*45R2%0.M%R75b35.A1%75@3*0,4-.%\0.@5+%R-7%50AH%-R%,H5+5%I0*35% +,750C+%H015%75A5.,*1%N55.%b30.,4R45M%N1%#0.M40%G0,4-.0*%ON-70,-745+2%0.M%075%S75+5.,5M%4.%,H5%AH07,%N5*-?%4.% ,57C+%-R%0MM4,4-.0*%N5.5R4,+%S57%Y / H%M5*4I575M%-.TS508<

'

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[1] %#-37A5%!1!+899:+!"#$%8%'()*+!","+"-+!%(-"&/(%+!*/'8%+0'%'("/+1.*2'&(2('3+4*/*8%'("/+5*26/"."7(*,%Z!"!c!^dcY -M5*cK57+4-.c&<)&T:T(T')%

[2] %#-37A5%#,70,5d5.%!-.+3*,4.@2%515*4V5M%!-+%-R%d5.570,4-.%Y -M5*%

[3] %$++3C5+%C-+,%75A5.%+0CS*5%-R%0I570@5+3CC57%-RRTS508%?H-*5+0*5%S74A5%R7-C%!$D#^%^$#D#%M0,0N0+5%

[4] %'F\D%!H4.-%#,3M1%P\T')';>;2%d6(/"+;%''*&3+1/*&73+0'"&%7*+<"=*&+<.%/'>+1/7(/**&2"-2@*2"&A+@*$"&%ZJ5A5CN57%'99&)%

!"#$%%*%&'()%$**+,-.%/012%#34,5%&')2%65785*512%!$%9:;):%%*%(')<==(<;>'%%*%?? ?<+,-70@50**40.A5<-7@%

$'&B%#1+,5C+%%*%%$D!E"0+%F5..%%*%%$*,04G0.-%%*%%650A-.%F-?57%%*%%!H5I7-.%'.57@1%#-*3,4-.+%%*%%J5510%'.57@1%

".57#1+%%*%%'.57K03*,%%*%'L4V5%%*%%J5N5.H0C%'.57@1%%*%%O*34V4A%'.57@1%%*%%DA5%'.57@1%%*%%D.57,40%'.57@1%

F-?57@5,4A+%%*%%F73M5.,%'.57@1%%*%%FKP%#-*07%%*%%#0C+3.@#JD%%*%%#3.,5AH%%*%%#3+,04.0C%%*%%Q,75C5F-?57%

F0@5%8%-R%<

%

! "#$%&' ( ) *$+%#', '+' - . #+/#$'+" 0' -1#+ "#$'21)#$" +)34#') *'
5+)6$+1'7 +8,93$#0' : #+ ; #$8'

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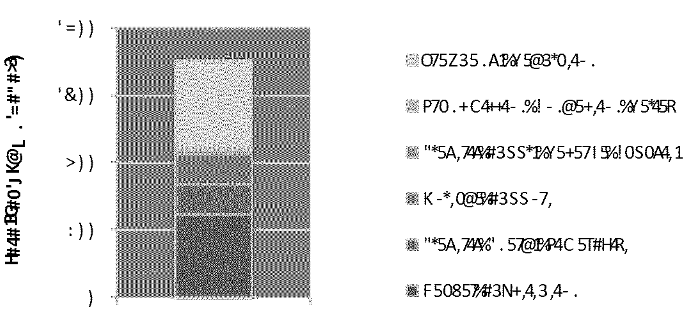
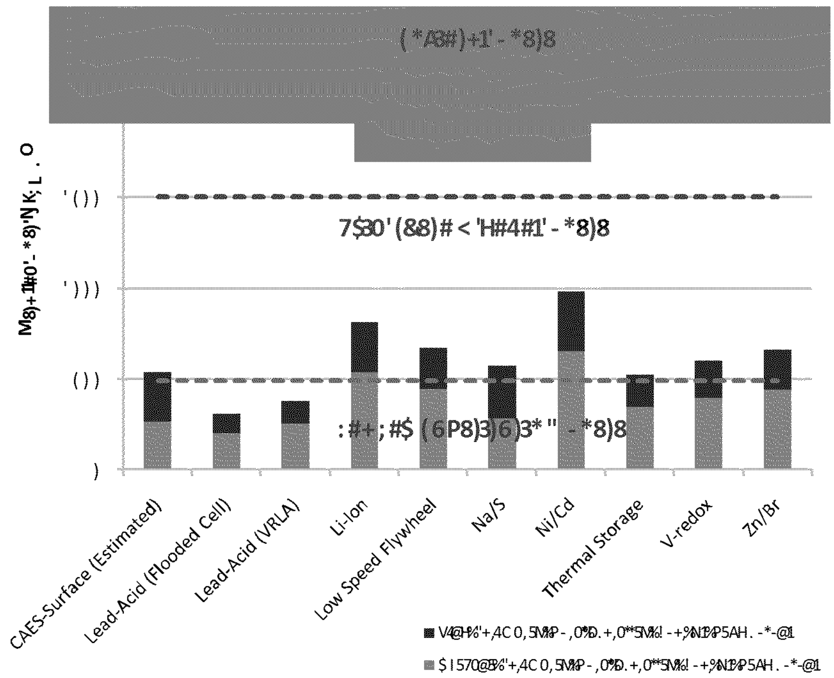
2003)3* " +1' (&8)# < '=#" #>3)8' *>' ! "#$%&' ( ) *$+%#'[?]



! "#$%&' ( ) *$+%#'38') . #'@ *8)' - *8), !>>#A)34#'B#8*6$A#'

/ H5 .%,H5+5%N5 . 5R4,+%075%R0A, -75M%4.%0 .M%A - C S075M%, -%,H5%, - ,0*%4. +,0**5M%A -+,%R-7%0%70 .@5%-R%5 . 57@1%+, -70@5% ,5AH . -*-@45+2%5 . 57@1%+, -70@5%5 C 57@5+%0+%0%A - C S75H5 . +4I 52%A - +,T5R5A,4I 5%+1+,5 C%75+- 37A5%%

9 *8831'96#1' (*A3#)+1C'7$30C+" 0' : #+ ;3"%' - *8)8'48D! "#$%&' ( ) *$+%#' - *8)8[EFGEE]



24 *30#0' - *8)8'B#+ 3G#0'

(*A3#)+1'H#4#1'

- UVU%W%$4%X 30*4,1%
- Y5 . 5 ? 0N*5+%D. ,5@70,4- %
- # C 07%,U74M%DC S*5 C 5 . ,0,4- %
- #,750 C*4. 5M%F57C4, ,4.@%

%

7$30' (&8)# < 'H#4#1'

- "*5A,74%' . 57@1%P4C 5T#H4R,%
- K -*,0@5%#3SS-7%
- "*5A,74%#3SS*1%Y5+57I5%! 0S0A4,1%
- P70 . +C4+4- .%! - .@5+,4- .%Y5*45R%
- O75Z35 . A1%Y5@3*0,4- %

: #+ ; #$'H#4#1'

- F50857%F*0 .%#3N+,4,3,4- %

%

%

PH5%N07+%4.%,H5%AH07%0N- I5%75S75+5 . ,%,H5%, - ,0*%4. +,0**5M%A -+,%S57%8 / H%-R%5 . 57@1%+, -70@5%A0S0A4,1%N1%C0[-7% +, -70@5%,5AH . -*-@1%0++3 C4.@%R-37%H -37+%-R%A0S0A4,1%R-7%50AH%PH5%75M%0+H5M%*4. 5%4.M4A0,5+%? H575%+, -70@5%A -+,+%

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[9] %#-37A5%#$G JD$%Y5S-7%#$G J&) ')T)>' (2%'#$%&' !( ) *%+&$!, *%) -$!".$/)%0)0) ' !1%02)!4$#$,0)5!+#2!6 +%7$)!8 *)$#)0+.!955$55 : $#)!1 ;02$24C%'157%W%U07,H% ! -75I%O5N7307@&) ')_%

[10] %$++3 C S,4- .+%$*%5 . 57@1%+, -70@5%,5AH . -*-@1%A-+,%+%H- ? .%075%. -7 C0*4`5M%R-7%0%R-37 TH -37%N%B70,4- .%%P5AH . -*-@1%A- C S07+- .%4%R-7%C -M57.%5 . 57@1%+, -70@5% +1+,5C+%- .*1%N3,%M-5+%- .%4. A*3M5%$3 C S5M%H1M7-%-7%H@HT+S55M%R*1 ? H55*+%? H4AH%075%. -%M5+4@. 5M%R-7%- .@%N%B70,4- .%S5084.@%0SS*4A0,4- .+%

[11] %#-37A5%$ I570@5%5+,4C 0,5M%, - ,0*%4. +,0**5M%A-+%5+,4C 0,5%R7- C%#0 .M40%Y5S-7%#$G J&))>T)9 ;>2%#3+0.% b%#AH-5 .3 .@%0 .M%]4C%"157%2%4$#$,0)<=*5)! >%+ : $? *%7!, *%4"@+. ;+)0#8%O5N7307@&)) >_%

!"#$%&'()*$+%#','+'-.#+/#$'+"0'-1#+"#$'21)#$"+)34#')*'5+)6$+1'7+8,93$#0':#+;#$8'

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07S%0,%A-+,%S074,1%?4,H%0%.0,370*@0+TR47S5M%S508S7%PH5%@755.%M0+H5M%4.5%4.M4A0,5+%,H5%@74M%+1+,5C%*5I5*%A-+,%0I-4M5M%?4,H%5.57@1%+,-70@5%*%4*%-,H57%?-7M+2%,H4*%4.5%4*%75S75+5.,0,4I5%-R%-,H57%750*%+1+,5C%A-+,+%,H0,%075%N-7.5%N1%5*5A,74A4,1%A3+,-C57+%O4.0**12%,H5%N*3S%077-?%75S75+5.,+%,H5%,-,0*%+-A45,0*%A-+,%0I-4M5M%N1%5.57@1%+,-70@5%24.A*3M4.@%4,+%ON4*4,1%,-%H5*S%0AH45I5%O0+C07%@74M%20A A5*570,5%0.M%R0A4*4,0,5%75.5?0N*5+%4.,5@70,4-.2%0.M%0I-4M%UVU%5C4++4-.+%

'

!"#$%&'()*$+%#'38'+'-1#+"#$'21)#$"+)34#')*'5+)6$+1'7+8,93$#0':#+;#$8'

U74M%+,-70@5%4M+S*0A5+%*5+%5RR4A45.,2%M47,457%S508S7%@5.570,4-.%N1%4C5T+H4R,4.@%C-75%5RR4A45.,2%A*50.57%N0+5T*-0M%@5.570,4-.%,%S508%S574-M+%PH4+%75+3*,+%4.%+3N+,0.,40*%+1+,5CT?4M5%04?%W30*4,1%N5.5R4,+%PH5%AH07,%N5*-?%A-CS075+%0A,30*%A07N-.%M4-L4M5%X!Y& +57I4A5%,574,-71%F50857%S*0.%@5.570,4-.%S7-M3A5+%R07%C-75%!Y&%5C4++4-.+%S57%Z/H%,H0.%N0+5*-0M%@5.570,4-.2%

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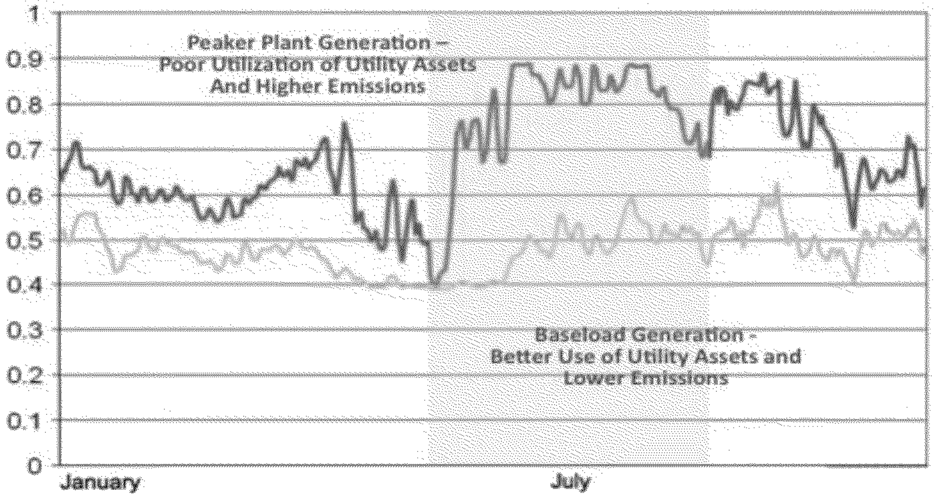

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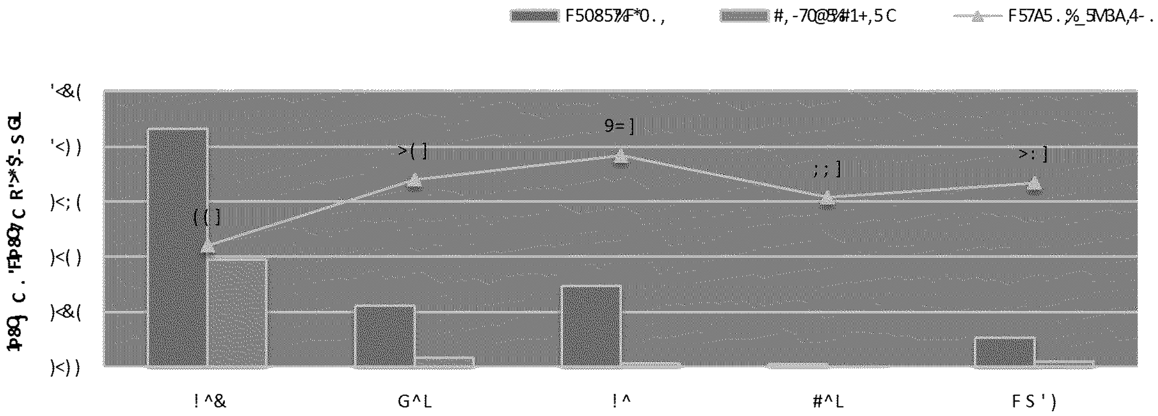

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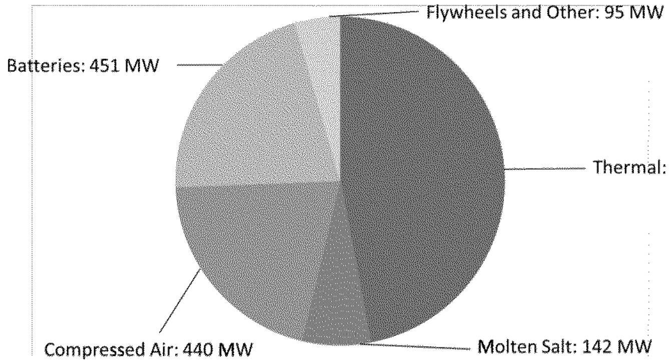

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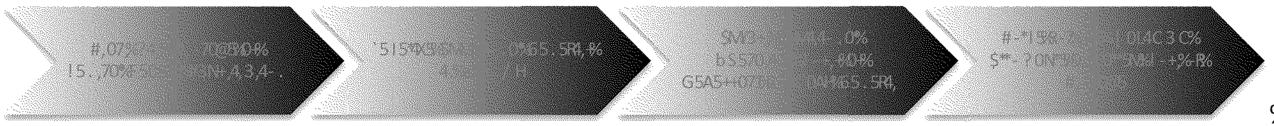

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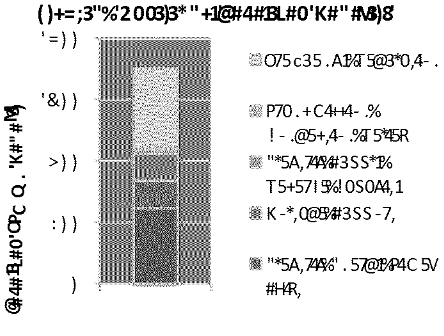

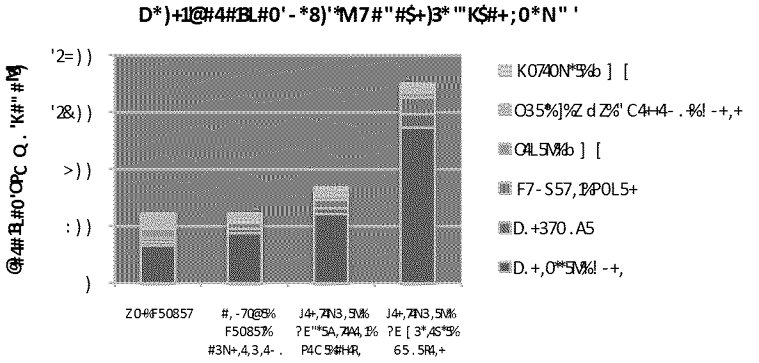

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ATTACHMENT 9

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The politics and policy of energy system transformation – explaining the German diffusion of renewable energy technology

Abstract
The politics and policy of energy system transformation – explaining the German diffusion of renewable energy technology

To arrest climate change, a transition to a low-carbon economy must take place quite rapidly, within a century at most. Thus, the rate of diffusion of new technologies such as those for the generation of electricity from renewable energy sources becomes a central issue. This article explores the reasons for the particularly rapid spread of two such technologies in Germany, wind turbines and solar cells. We trace this diffusion to the nature of the policy instruments employed and to the political process which led to the adoption of these instruments. The analysis demonstrates how the regulatory framework is formed in a 'battle over institutions' where the German parliament, informed and supported by an advocacy coalition of growing strength, backed support policies for renewables sourced electricity against often reluctant governments and the opposition from nuclear and coal interests. It also demonstrates that this major political and environmental achievement carries a modest price if we consider total costs to society, i.e. including both subsidies to coal and the negative external economies of coal.

Keywords: Renewable energy; Regulatory framework; Market creation

1. Introduction[1]

Fossil fuels constitute the dominant source of energy in the world, contributing about 80 per cent (91,000 TWh) of total primary energy supply and 64 per cent (9,400 TWh) of electricity generation in 1999. This dominance is associated with clear environmental and climate challenges. A wider use of renewable energy technology is seen as one way of meeting these challenges. For instance, the European Union aims at increasing the share of renewable energy of the supply of electricity from about 14 per cent in 1997 to 22 per cent by 2010 (Lauber, 2002). To obtain this target (reduced to 21 per cent as a result of Eastern European enlargement), and go beyond it later on, a range of renewable energy technologies need to be diffused.

Many of these technologies are available in an early form after several decades of experimentation, but their impact on the energy system is hitherto marginal. If these, and their successors, are to have a substantial impact on the climate issue, powerful government policies must promote their diffusion and further development over several decades to come. While many governments claim to support the diffusion of renewables, the actual rate of diffusion of new technologies in the energy system varies considerably between countries. Drawing on the literature in 'economics of innovation' or related fields, it is possible to 'explain' differences in rates of diffusion by, inter alia, the nature of policies pursued. Immediately, the next question follows: Why do then some countries choose policies which apparently are superior in terms of inducing transformation whereas other countries choose policies which work less well? On this issue, 'economics of innovation' has little to add, as much of the discussion on policy takes a 'rationalistic' approach attempting to pinpoint the 'best' way.

Policy-making is, however, not a 'rational' technocratic process but rather one that appears to be based on such things as visions and values, the relative strengths of various pressure groups, perhaps on beliefs of 'how things work' and on deeper historical and cultural influences. What then are the political (in a broad sense) determinants and 'boundaries' of policy making and, therefore, of the rate at which the energy sector is transformed?

In this paper, we combine an 'economics of innovation' analysis (linking diffusion patterns to actual policies) with a 'politics of policy' analysis (explaining the choice of policies in the larger political context). In our first attempt to do so, we will focus on the case of Germany. Germany is one of the leading countries in terms of both the supply and use of two key renewable energy technologies: wind turbines and solar cells. Our objective is to explain the high rate of diffusion of wind turbines and solar cells in Germany not only by the particular features of the German regulatory framework in the energy sector but also by the ideas and processes which led various political bodies to adopt that framework. In the European debate, much emphasis is given to the costs of implementing key features of that framework, in particular the Feed-in Law of 1990 and its successor, the Renewable Energy Sources Act of 2000. We will therefore also make a preliminary assessment of both the financial flows and the social costs associated with various energy technologies in Germany.

The paper is structured in the following way. Section 2 contains a brief introduction to the technologies studied as well as some elements of an analytical framework for studying relatively early phases of diffusion and transformation processes. In section 3, we outline German politics and policies on renewables and how they have impacted on the diffusion process for wind and solar power. Section 4 contains a discussion of the financial flows and social costs of these policies. Our main conclusions are given in section 5.

2. Elements of an analytical framework[2]

Large-scale hydropower and combustion of different types of biomass currently provide the bulk of the energy supplied by renewable energy sources. In 1999, these supplied roughly 2,600 TWh and 160 TWh of electricity respectively worldwide (UNDP, 2000;[3] IEA, 2001). In addition to these, the 'new' renewables – e.g. wind turbines and solar cells – are now diffusing at a quite rapid rate.[4]

Figures 1 and 2 show the global diffusion of wind turbines and solar cells. After an extensive period of experimentation, dating back decades [5] and lasting throughout the 1980s, the global stock of *wind turbines* grew very rapidly during the period 1990-2002 and reached a capacity of 32 037 MW. The stock of *solar cells* also grew at a high rate but the stock was more limited, 2 407 MW in 2002. For both technologies, the bulk of the stock was installed in the period 1995-2002. In other words, we have been witnessing what may be the beginnings of a take-off period in the long-term diffusion of these technologies.

Whereas the share of these technologies in the global energy supply is marginal at present – less than 0.5% of the 15,000 TWh of electricity generated in the world (Jacobsson and Bergek, 2003) – there are visions of wind power accounting for ten per cent of the world's electricity supply and of solar cells supplying one per cent by 2020 (EWEA et al., 1999, Greenpeace and EPIA, 2001). The real issue is no longer the technical potential of these (and other) renewable energy technologies, but how this potential can be realised and substantially contribute to a transformation of the energy sector.

Yet, a large-scale transformation process of this kind requires far-reaching changes, many of which date back several decades and involve political and policy support in various forms in pioneering countries. Drawing on a rich and very broad literature, we will outline elements of an analytical framework [6] that captures some key features of early phases of such transformation processes.

Some characteristics of such phases may be found in the literature on industry life cycles (e.g. Afuah and Utterback, 1997; Utterback and Abernathy, 1975; Van de Ven and Garud, 1989; Utterback, 1994; Klepper, 1997; Bonaccorsi and Giuri 2000). It emphasises the existence of a range of competing designs, small markets, many entrants and high uncertainty in terms of technologies, markets and regulation. We need, however, to understand the conditions under which this formative stage, with all its uncertainties, emerges in a specific country. We will outline four key conditions, or features, of early parts of such processes. These are institutional changes, market formation, the formation of technology-specific advocacy coalitions, and the entry of firms and other organisations.

First, as emphasised in the literature on 'economics of innovation' *institutional change* is at the heart of the process (Freeman and Louca, 2002). It includes alterations in science, technology and educational policies. For instance, in order to generate a range of competing designs, a prior investment in knowledge formation must take place and this usually involves a redirection of science and technology policy well in advance of the emergence of markets. Institutional alignment is also about the value base (as it influences demand patterns), market regulations, tax policies as well as much more detailed practices which are of a more immediate concern to specific firms, as discussed, for instance, by Maskell (2001). The specific nature of the institutional framework influences access to resources, availability of markets as well as the legitimacy of a new technology and its associated actors. As argued in the literature of both 'innovation systems' (e.g. Carlsson and Jacobsson, 1997) and 'transition management' (Rotmans et al., 2001), the nature of the institutional framework may therefore act as one of many mechanisms that obstruct the emergence of a formative stage and its evolution into a growth phase. Firms, therefore, compete not only in the market for goods and services but also to gain influence over the institutional framework (Van de Ven and Garud, 1989; Davies, 1996).

Second, institutional change is often required to *generate markets* for the new technology. The change may, for instance, involve the formation of standards, such as the Nordic telecommunication operators' decision to share a common standard (NMT) for mobile telecommunications. In the formative phase, *market formation* normally involves exploring niche markets, markets where the new technology is superior in some dimension. These markets may be commercial and involve unusual selection criteria (Levinthal, 1998) and/or involve a government subsidy. A 'protected space' for the new technology may serve as a 'nursing market' (Ericsson and Maitland, 1989) where learning processes can take place and the price/performance of the technology improve (see also Porter, 1998). Nursing markets may, through a demonstration effect, also influence preferences among potential customers. Additionally, they may induce firms to enter, provide opportunities for the development of user-supplier relations and other networks, and, in general, generate a 'space' for a new industry to evolve in.

The importance of early markets for learning processes is not only emphasised in management literature but also in the policy oriented literature on 'Strategic Niche Management'. A particularly clear statement of this is found in Kemp et al. (1998, 184):

> Without the presence of a niche, system builders would get nowhere..Apart from demonstrating the viability of a new technology and providing financial means for further development, niches help building a constituency behind a new technology, and set in motion interactive learning processes and institutional adaptation.that are all-important for the wider diffusion and development of the new technology.

Third, whereas individual firms, and related industry associations, may play a role in competition over institutions (Feldman and Schreuder, 1996; Porter, 1998), such actors may be but one part of a broader constituency behind a specific technology. The build up of a constituency involves the 'entry' of other organisations than firms. It may involve universities but also non-commercial organisations (e.g. Greenpeace). Unruh (2000, 823) underlines the existence of a range of such organisations and the multitude of roles they play.

> ..users and professionals operating within a growing technological system can, over time, come to recognize collective interests and needs that can be fulfilled through establishment of technical..and professional organisations.These institutions create non-market forces.through coalition building, voluntary associations and the emergence of societal norms and customs. Beyond their influence on expectations and confidence, they can further create powerful political forces to lobby on behalf of a given technological system.

The centrality of the formation of constituencies is well recognised in the political science literature, in particular in the literature on networks (Marsh and Smith, 2000; Rhodes, 2001). Thus, Sabatier (1998) and Smith (2000) argue that *advocacy coalitions,* made up of a range of actors sharing a set of beliefs, compete in influencing policy. For a new technology to gain ground, *technology-specific coalitions* need to be formed and to engage in wider political debates in order to gain influence over institutions and secure institutional alignment. As part of this process, advocates of a specific technology need to build support among broader advocacy coalitions to advance the perception that a particular technology, e.g. solar cells or gas turbines, answers wider policy concerns. Development of joint visions of the role of that particular technology is therefore a key feature of that process. Hence, the formation of "political networks" sharing a certain vision and the objective of shaping the institutional set-up is an inherent part of this formative stage.

Fourth, *entry of new firms* is central to the transformation process. Each new entrant brings knowledge, capital and other resources into the industry. New entrants experiment with new combinations, fill 'gaps' (e.g. become a specialist supplier) or meet novel demands (e.g. develop new applications). A division of labour is formed and further knowledge formation is stimulated by specialisation and accumulated experience (e.g. Smith, 1776; Young, 1928; Stigler, 1951; Rosenberg, 1976). Finally, early entrants raise the returns for subsequent entrants in a number of ways, i.e. positive external economies emerge (Marshall, 1890; Scitovsky, 1954). In addition to the conventionally related sources of external economies (e.g. build up of an experienced labour force and specialised suppliers of inputs) early entrants strengthen the 'political' *power* of a technology-specific advocacy coalition and provide an enlarged opportunity to influence the institutional set-up. Early entrants also drive the process of *legitimation* of a new field, improving access to markets, resources etc. for subsequent entrants (Carroll (1997) and resolve underlying technical and market uncertainties (Lieberman and Montgomery, 1988).

The time span involved in an early phase where these four features emerge may be very long. This is, for instance, underlined in a recent study of Israel's 'Silicon Wadis,' which began a rapid period of growth in the 1990s after a history starting in the 1970s (de Fontenay and Carmel, 2001). Other examples are given in Geels (2002) and in Carlsson and Jacobsson (1997a).

A *'take-off'* into a rapid growth phase may occur when investments have generated a large enough, and complete enough, system for it to be able to 'change gear' and begin to develop in a self-sustaining way (Carlsson and Jacobsson, 1997; Porter, 1998). As it does so, a chain reaction of powerful *positive feedback loops* may materialise, setting in motion a process of cumulative causation. Indeed, as pointed out long ago by Myrdal (1957), these virtuous circles are central to a development process – as these circles are formed, the diffusion process becomes increasingly self-sustained and characterised by autonomous dynamics (Rotmans et al., 2001), often quite unpredictable in its outcome. All the four features of the formative phase are involved in such dynamics. For instance, the emergence of a new segment may induce entry by new firms, which strengthen the political power of the advocacy coalition and enables further alignment of the institutional framework (which, in turn, may open up more markets and induce further entry etc.).

Under what conditions a 'take-off' takes place seems to be extremely difficult to predict. A necessary condition is, however, that larger markets are formed – there must be an underlying wave of technological and market opportunities. Some ICT clusters have become successful by linking up to the US market (Breshanan et al., 2001) whilst the Nordic technological systems in mobile telephony grew into a second phase with the European GSM standard. As we shall see below, it has been alterations in the *regulatory frameworks* that triggered a set of actions and reactions and propelled the diffusion process in the cases of wind power and solar cells in Germany. At the heart of the story that is to be told lies a 'battle over institutions'.

3. Wind energy and solar cells in Germany: politics, policies and their impact on diffusion

This section will deal with basic values and beliefs as well as processes leading up to policy-making, the attendant policies, the impact of these policies on technology diffusion and subsequent feed-back loops to policy making. Although we are analyzing what with hindsight is an early phase in the diffusion process, we shall divide this into three sub-phases. 1974 to the late 1980s was a formative phase for both wind and solar cells. Important decisions in favour of market creation were taken beginning in 1988, and this policy was implemented during subsequent years. 1990 brought a first take-off for wind while continuing the formative phase for solar cells. 1998 reinforced the take-off for wind and began a take-off period for solar cells. These three sub-phases are clearly seen in Figures 3 and 4, which portray the diffusion of these technologies in Germany. Whereas Germany accounted for a less than one percent share of the global stock of these technologies in 1985 and 1990 respectively, it came to play a prominent role in the global diffusion from the early 1990s. Indeed, at the end of 2002, Germany had more than one third of the global stock of wind turbines - 12.001 out of 32.037 MW of installed capacity - and about one ninth of the stock of solar cells, approximately 275 MWp out of 2.403 MWp (See figures 1 to 4; *Solarthemen* 158, 30 April 2003).
Figures 1-4 about here

3.1: 1974 to 1988 – a formative phase of wind and solar power

The energy crises of the 1970s produced major rethinking in Germany as in many other countries. The main emphasis there was to increase government support for hard coal and nuclear power use (Schmitt, 1983; Kitschelt, 1980). From the mid-1970s, however, nuclear power became increasingly controversial with the public; its rapid expansion led to many bitter confrontations and a policy of repression until the end of the decade. Many believed that the government should instead bank on energy efficiency and renewable energy. A first *Enquete Commission* [7] of the German parliament in 1980 recommended effficiency and renewables as first priority but also the maintenance of the nuclear option (Meyer-Abich and Schefold, 1986). In 1981, the Federal Ministry of Research and Technology commissioned a five-year study, which drew a strong echo in the media when it was published around the time of the Chernobyl accident. It concluded only that reliance on renewables and efficiency would be compatible with the basic values of a free society, and that it would be less expensive than the development of a plutonium-based electricity supply as envisioned at that time (Meyer-Abich and Schefold, 1986). Against this background of strong pressure from public opinion, R&D for renewable energy sources was raised to a significant level – not as significant per capita as in other countries such as Sweden, Denmark and the Netherlands, but larger in total amount. In 1974, annual spending started with about DM 20 million. It reached a peak of DM 300 million in 1982 – the year when the government passed from the social democratic/liberal to a conservative/liberal coalition under chancellor Kohl – and declined thereafter to a low point of 164 million in 1986 (the year of the Chernobyl accident). Further decline had been scheduled but was reversed at that point (Sandtner et al., 1997). Much publicly financed R&D was intended for developing off-grid renewable energy technologies for export to the Third World, not for the domestic market (Schulz, 2000).
Until the end of the 1980s and in fact beyond, renewable energy faced a political-economic electricity supply structure that was largely hostile. The electricity supply system was dominated by very large utilities relying on coal and nuclear generation. The utilities were opposed to all small and decentralised forms of generation, which they deemed uneconomic

and foreign to the system. The two key ministries – Economic Affairs on one hand, Research and Technology on the other - offered only limited help. The Ministry of Economic Affairs was (and still is) in charge of utilities and, in fact, their chief ally. Both the Social Democratic-Liberal (before 1982) and the Conservative-Liberal[8] governments (1982-1998) strongly supported nuclear and coal. This is clearly seen in the allocation of R&D funds, where R&D funding to nuclear power and fossil fuels dwarfed that of renewable energy technology (Figure 5).

Figure 5 about here
(Energy R&D in Germany, 1974-2002)

Moreover, during the oil crisis, the government created powerful incentives for utilities to use otherwise non-competitive domestic hard coal. These incentives were paid out of a government fund financed by a surcharge or special tax on final customers' electricity prices. This surcharge varied between 3.24 per cent of that price in 1975-76 and 8.5 per cent in 1989 (Bundesverfassungsgericht, 1994). At the same time, the Ministry of Economic Affairs – normally in charge of market creation programs – did little for renewable energy sources. It only made use of the general competition law to oblige the utilities (then operating as territorial monopolies) to purchase electricity from renewable energy sources produced in their area of supply at avoided costs. However, the large utilities interpreted this so narrowly (as avoided fuel costs only) that the obligation had little effect. [9] The ministry resisted all demands for market formation with the slogan that energy technologies had to prove themselves in the market and that it was not prepared to subsidise technologies that were not mature.

At the same time, the Ministry of Research – the former Ministry of Nuclear Affairs renamed in 1962, whose tasks now came to include renewables – viewed its responsibility as one of only supporting research and development, and to a smaller extent demonstration. It was more generous in funding nuclear demonstration projects. By 1980, it had spent about DM 13 billion on nuclear RD&D (Kitschelt, 1980; Zängl, 1989). Under the prevailing distribution of responsibilities – which was jealously observed by the much more powerful Ministry of Economic Affairs (Ristau, 1998) – it was allowed to support renewable energy technologies only in pre-market phases. There was little opportunity or willingness to bridge the gap between research prototypes and market-competitive products.

Yet, in this largely unfavorable political context, institutional changes occurred which began to open up a space for wind and solar power; a space which proved to be of critical importance for the future diffusion of these renewables. This institutional change largely related to the formation of government funded R&D programs for these technologies.

These programmes provided opportunities for universities, institutes and firms to search in many directions, which was sensible given the underlying uncertainties with respect to technologies and markets. Some programmes may have pursued ambivalent goals; thus one of the purposes of the GROWIAN project of a large (several MW) wind turbine was allegedly to demonstrate that wind power was not viable (Heymann, 1999). However, the wind power R&D programme was large enough to finance most projects applied for and flexible enough to finance most types of projects (Windheim, 2000a). In the period 1977-1989, about 40 R&D projects were granted to a range of industrial firms and academic organisations for the development or testing of small (e.g. 10 kW) to medium sized (e.g. 200-400 kW) turbines (elaboration on Windheim, 2000b).[10]

Much the same applied to R&D in solar cells. In the period 1977-89, as many as 18 universities, 39 firms and 12 research institutes received federal funding (Jacobsson et al., 2002).[11] Although the major part of the research funding was directed towards cell and module development and the prime focus was on crystalline silicon cells, funds were also given to research on several thin-film technologies.[12] In addition, R&D funds were allocated to the exploration of a whole range of issues connected to the application of solar cells, such as the development of inverters. As a consequence, and in spite of the fringe status of that R&D, a broad academic cum industrial knowledge base began to be built up about twenty-five years ago for both wind turbines and solar cells.

In the 1980s, a set of demonstration programmes became part of the R&D policy. Investments in wind turbines were subsidised by several programmes (Hemmelskamp, 1998). At least fourteen German suppliers of turbines received funding for 124 turbines in the period 1983-1991 (elaboration on Windheim, 2000b).[13] This programme constituted an important part of the very small national market in the 1980s – total installed power was just 20 MW by the end of 1989 (Durstewitz, 2000). An early niche market was also found in 'green' demand from some utilities – reflecting the strength of the green movement (Reeker, 1999) – and from environmentally concerned farmers (Schult and Bargel, 2000; Tacke, 2000).

In solar cells, the first German demonstration project took place in 1983. This was wholly financed by the federal government and had an effect of 300 kW_p, which was the largest in Europe at that time. In 1986, it was followed by a demonstration programme which by the mid-1990s had contributed to building more than 70 larger installations for different applications. Yet, by 1990, the accumulated stock amounted to only 1.5 MW_p (see Figure 4). Although the demonstration programme had only a minor effect in terms of creating a 'protected space', it was effective as a means of enhancing the knowledge base with respect to application knowledge. Hence, by that time, learning had taken place not only among four firms which actually had entered into solar cell production (e.g. AEG, MBB and Siemens) but also to some extent 'downstream' in the value chain.

In sum, this formative phase was dominated by institutional change in the form of an R&D policy that began to include, at the fringe, R&D in renewables. Although small in relation to R&D in nuclear and other energy technologies, it allowed for a small space to be opened for wind and solar power in which a range of firms and academic departments began a process of experimentation and learning. Small niche markets were formed and a set of firms were induced to enter.

In addition to these firms and universities, a range of other organisations were set up, organisations which later were to become key actors in advocacy coalitions for wind and solar power. These included conventional industry associations such as the German Solar Energy Industries Association, which was founded in 1978 (Bundesverband Solarindustrie, 2000). As importantly, environmental organisations that were independent of industry grew up to provide expertise and visions of the future. For instance, in 1977, at the height of the anti-nuclear power controversy, actors of the green movement set up the Institute of Ecology (*Öko-Institut*) in Freiburg to provide counter-expertise in their struggle with governments and utilities. This institute became very important for coming up with proposals for the development of renewable energy policies later on. In a similar vein, Förderverein Solarenergie, started in 1986, in 1989 developed the concept of 'cost covering payment' for electricity generated by renewable energy technology, a concept which was later applied in various feed-in laws at federal and local levels. A third type of association is Eurosolar, founded in 1988, which is an organisation for campaigning *within* the political structure for support of renewables and which is independent of political parties, commercial enterprises and interest groups, yet counts several dozen members of the German parliament in its ranks (not only from red-green).

3.2: 1988-1998 - take off for wind power but not for solar power

The accident in Chernobyl in 1986 had a deep impact in Germany. Public opinion had been divided about evenly on the question of nuclear power between 1976 and 1985. This changed dramatically in 1986. Within two years, opposition to nuclear power increased to over 70 per cent, while support barely exceeded 10 per cent (Jahn, 1992). The social democrats committed themselves to phasing out nuclear power; the Greens demanded an immediate shutdown of all plants.

Also in 1986, a report by the German Physical Society warning of an impending climate catastrophe received much attention, and in March 1987 chancellor Kohl declared that the climate issue represented the most important environmental problem (Huber, 1997). A special parliamentary commission was set up to study this matter – the *Enquetekommission* on climate. The commission worked very effectively in a spirit of excellent co-operation between the parliamentary groups of both government and opposition parties. There was general agreement that energy use had to be profoundly changed. The matter was given increased urgency by the fact that the price of oil had declined again, so that further increases of fossil fuel consumption had to be expected unless serious measures were taken; at the same time, the price gap between renewable energy technologies and conventional generation grew larger (Kords 1996; Ganseforth 1996).

A series of proposals for institutional change were formulated which included an electricity feed-in law for generation from renewables (Schafhausen, 1996). Pressure from parliament on the government to take substantial steps in favour of renewables increased, as evidenced by a variety of members' bills (Deutscher Bundestag, 1987, 1988a, 1988b, 1989, 1990a and 1990b). This was obviously reflecting a high level of public concern with this issue at that time. The Ministry of Economic Affairs tried to counteract these efforts ("no subsidisation of technologies unfit for the market") but failed to persuade all the deputies of the government coalition. Nor was it able to induce the utilities to create framework conditions more favourable for the expansion of renewables on a voluntary basis.

Eventually the government more or less reluctantly – support only came from the Environment Ministry under Töpfer – adopted several important measures. In 1988, the Ministry of Research launched two large demonstration cum market formation programmes. A first was directed at wind power and initiated in 1989. Initially, it aimed at installing 100 MW of wind power – a huge figure compared to the stock of 20 MW in 1989. Later, it was expanded to 250 MW. The programme mainly involved a guaranteed payment per kWh electricity produced of €0.04/kWh, later reduced to 0.03..[14] The second demonstration cum market formation measure was the 1.000 roofs programme for solar cells. Furthermore, the legal framework for electricity tariffs was modified in such a way as to allow compensation to generators of renewables sourced electricity above the level of avoided costs. Finally, the Electricity Feed-in Law was adopted, which was originally conceived mainly for a few hundred MW of small hydropower (Bechberger, 2000).

Remarkably, the Feed-in Law – the most important measure since it was conceived for a longer term – was adopted in an all-party consensus (though social democrats and greens wanted to go further in the support of renewables sourced electricity).[15] As mentioned above, the basic concept of the Feed-in Law was put forward by several associations - Förderverein Solarenergie (SFV), Eurosolar and an association organising some 3.500 owners of small hydro power plants, many of whose members were politically conservative and able to effectively campaign for the new law in a larger association organising small and medium-sized firms. It seems that passing the law did not require a large political effort, despite the opposition of the utilities which were not entitled to receive any benefits under this law if they invested themselves in the new technologies (Ahmels, 1999; von Fabeck, 2001; Scheer, 2001). But then a few hundred MW hydropower was hardly a serious matter, and in addition the big utilities were at that time absorbed in taking over the electricity sector of East Germany in the process of reunification (Richter, 1998).
The Feed-in Law required utilities to connect generators of electricity from renewable energy technology to the grid and to buy the electricity at a rate which for wind and solar cells amounted to 90 per cent of the average tariff for final customers, i.e. about DM 0.17. [16] Together with the 100/250 MW programme and subsidies from various state programmes (DEWI, 1998), the feed-in-law gave very considerable financial incentives to investors, although less for solar power since its costs were still very high compared to the feed-in rates. One of the declared purposes of the law was to 'level the playing field' for renewables sourced electricity by setting feed-in rates at levels that took account of the external costs of conventional power generation. In this context, the chief member of parliament supporting the feed-in bill on behalf of the Christian Democrats in the Bundestag mentioned external costs of about 3-5 Eurocents per kWh for coal-based electricity (Deutscher Bundestag, 1990c).
These incentives stimulated the formation of markets and had three effects. First, it resulted in an 'unimaginable'[17] market expansion from about 20 MW in 1989 to close on 490 MW in 1995 (BWE, 2000).[18] Second, it led to the emergence of learning networks which developed primarily between wind turbine suppliers and local components suppliers due to the need of adapting the turbine components to the particular needs of each turbine producer. The benefits of learning also spilled over to new entrants (induced by market growth), since these could rely on a more complete infrastructure. Third, it resulted in a growth in the 'political' strength of the industry association organising suppliers and owners of wind turbines who were now able to add economic arguments to environmental ones in favour of wind energy.

However, when the Feed-in Law began to have an impact on the diffusion of wind turbines, the bit utilities started to attack it both politically and in the court system (basically on constitutional grounds) – unsuccessfully, as it were. This reflected more than just opposition to small and decentralised generation. First, no provision had been made to spread the burden of the law evenly in geographical terms; this came only in 2000. Second, the utilities were by this time marked by the experience of politically dictated subsidies for hard coal used in electricity generation. These subsidies had grown from €0.4 billion in 1975, the year the 'coal penny' was introduced, to more than €4 billion annually in the early 1990s (see sec. 3.1 above). Two thirds of this was covered by a special levy on electricity, one third had to be paid by the utilities directly but was also passed on to the consumers.[19]
Political efforts to change the law seemed at first more promising. In 1996, utilities association VDEW lodged a complaint with DG Competition (the subdivision of the European Commission which looks after fair competition) invoking violation of state-aid

rules. The Ministry of Economic Affairs then proposed to reduce rates on the occasion of an upcoming amendment (the law had to be changed in any case in order to spread the burden of feed-in payments more evenly in geographical terms, and also because of liberalisation), a measure supported by DG Competition. Even though the notification of the Feed-in Law to the European Commission had not drawn an adverse reaction right after its adoption, DG Competition now argued that feed-in rates should come down substantially along with costs, addressing particularly wind power (Salje, 1998; Hustedt, 1998; Advocate General Jacobs, 2000). The Ministry of Economic Affairs was happy enough with this support; its official line was that renewable energies were only "complementary" and could not pretend to replace coal and nuclear generation.

All this led to insecurity for investors and stagnating markets for wind turbines from 1996 to 1998. Indeed, climate policy had suffered a general setback at the governmental level due to the financial and other problems resulting from German reunification (Huber, 1997). However, the issue was still strong with public opinion. Thus, a survey conducted in 1993 in 24 countries showed that concern over global warming was greatest in Germany (Brechin, 2003).

In any event, the big utilities political challenge to the Feed-in Law failed in parliament (Ahmels, 1999; Molly, 1999; Scheer, 2001). In 1997, the government proposal to reduce feed-in rates mentioned above led to a massive demonstration bringing together metalworkers, farmer groups and church groups along with environmental, solar and wind associations; the Association of Investment Goods Industry VDMA gave a supportive press conference (Hustedt, 1997; Hustedt, 1998). The government failed to persuade even its own MPs. In a committee vote, the government proposal lost out by a narrow vote of eight to seven, and it seems that as many as 20 CDU/CSU members were determined to vote against the new rates in the plenary (Scheer, 2001). Clearly the new technology had by now acquired substantial legitimacy. As one CDU member and executive of the wind turbine industry put it: "In this matter we collaborate with both the Greens and the Communists" (Tacke, 2000). The Feed-in Law was now incorporated in the Act on the Reform of the Energy Sector of 1997 which transposed the EU directive on the internal market for electricity.

When it became clear that the feed-in rates would remain unchanged, this removal of uncertainty resulted not only in a further expansion in the market for wind turbines (see Figure 3), but also in the entry of larger firms into the wind turbine industry as well as into the business of financing, building and operating wind farms, strengthening the advocacy coalition yet again.

The second market introduction cum demonstration programme of the research ministry was focused on small solar cell installations, the 1.000 roofs programme, for which it provided an investment aid of 60 to 70 per cent. Eventually, the programme led to the installation of more than 2.200 grid-connected, roof-mounted installations with an effect of 5.3 MW_p by 1993 (IEA, 1999; Staiss and Räuber, 2002). Whereas the 1.000 roof program was successful, the market formation that it induced was not large enough to justify investments in new production facilities for the solar cell industry, in particular as the industry was running with large losses (Hoffmann, 2001). The industry now expected that there would be a follow-up to the 1.000 roof programme, but no substantial programme emerged (Brauch, 1997). In 1993, Eurosolar proposed a 100.000 roof programme that in the subsequent year was taken up by the Social Democrats (Hermann Scheer, the first president of Eurosolar, is himself a Social Democratic MP). This proposal was, however, not supported by the party groups of the (Conservative/Liberal) government coalition (Scheer, 2001). If the industry was to survive, market creation had to come from other quarters. This led to intensified efforts to mobilise other resources, a process which demonstrated the high level of legitimacy that solar PV enjoyed in German society.

The most important help came from municipal utilities. In 1989 the federal framework regulation on electricity tariffs – the tariffs themselves are set at the *Länder* level – was modified in such a way as to permit utilities to conclude cost-covering contracts with suppliers of electricity using renewable energy technologies, even if these full cost rates exceeded the long-term avoided costs of the utilities concerned. On this basis, local activists petitioned local governments to enforce such contracts on the utilities. After much effort, most *Länder* expressly allowed such contracts, and several dozen cities opted for this model, including Bonn and Nuremberg. As the process first started in Aachen, this is known as the Aachen model (Solarförderverein, 2002; Staiss and Räuber, 2002).[20] It was carried by many activist groups and to some extent co-ordinated by some of the new associations such as Eurosolar or SFV (Solarenergie-Förderverein).

Additional help came from some of the Länder, which had their own market introduction programmes, the most active being North Rhine-Westphalia. Some states acted through their utilities, which would subsidise solar cells for special purposes, e.g. schools (Bayernwerk in Bavaria, or BEWAG in Berlin). Some offered "cost-oriented rates" which however remained below the level of full cost rates (thus HEW in Hamburg). Finally, in a major effort, Greenpeace gathered several thousand orders for solar cell rooftop "Cyrus installations" (Ristau, 1998). Due to these initiatives, the market did not disappear at the end of the 1.000 roofs programme but continued to grow (see figure 4).

Even though the size of the market was quite limited, these initiatives had two significant effects. First, they induced a number of new, often small firms to enter into and enlarge the industry. Among these, we find both module manufacturers and integrators of solar cells into facades and roofs, the latter moving the market for solar cells into new applications. Second, the large number of cities with local feed-in laws and a proliferation of green pricing schemes revealed a wide public interest in increasing the rate of diffusion – the legitimacy of solar power was apparent. Various organisations could point to this interest when they lobbied for a programme to develop yet larger markets for solar cells. As mentioned above, Eurosolar proposed a programme to cover 100.000 roofs in 1993 and, since 1996, the German Solar Energy Industries Association had worked towards the realisation of such a programme (Bundesverband, 2000).[21]

Lobbying by the German solar cell industry also intensified. Siemens had at this time already started its production in the US and a second producer, ASE, had the opportunity of doing so with an acquisition of Mobil Solar. To continue production in Germany without any prospects of a large home market would clearly be questionable from a firm's point of view. ASE threatened at this time to move abroad if a market expansion did not take place (Hoffmann, 2001). A promise of a forthcoming programme was then given and ASE decided to invest in a new plant in Germany, manufacturing cells from wafers produced with a technology acquired from Mobil Solar. Production started in mid 1998 (ASE Press Release, 1998) in a plant with a capacity of 20 MW (Hoffmann, 2001).

The decision to locate production in Germany implied a dramatic increase in the German industry's solar cell production. A second major investment was Shell's entry into the German solar cell industry through its investment in a new plant in Gelsenkirchen in 1998 (9.5 MW, Stryi-Hipp 2001). Here too, a dialogue with policy makers preceded the investment

(Zijlstra, 2001). Hence, in 1998, two major investments were made which greatly expanded capacity in the German solar cell industry.

In sum, the initial 'space' given to wind and solar power in the 1970s and 1980s was now enlarged. In part, this was due to external changes (Chernobyl and the climate change debate) mediated by public awareness and the acceptance of the necessity to change the energy system. But it was also a result of the initial investments in the first formative period. Out of those investments came not only an initial knowledge base, but also an embryonic advocacy coalition consisting of industry associations, an infant industry and various interest organisations. A positive feed-back from those early investments resulting in an ability of this coalition to shape further institutional change can be discerned (1990 Feed-in Law). Further feed-back loops from market formation, through entry of various organisations, to an enhanced political power of the coalition and an ability to defend favourable institutions (which then led to further market formation, entries etc.) was a key feature of the subsequent diffusion process for wind power in the 1990s. For solar power, the process of market formation was made more difficult by the high cost of solar power but through an intensive work by the advocacy coalition, where the interest organisations Eurosolar and Förderverein Solarenergie plus Greenpeace played a key role, local market formation programmes were initiated and these were to become precursors to larger, federal programmes in the subsequent phase.

3.3 1998 to 2003 – take off for solar power, continued growth for wind power and new political challenges

In 1998, the Social Democratic/Green coalition which replaced the Conservative-Liberal government committed itself to a market formation programme for solar cells as called for by the PV industry and earlier on by Eurosolar and other organisations. The coalition agreement contained commitments to the introduction of an eco-tax on energy, to legislation improving the status of renewable energy, a 100.000 roof programme for solar cells and a negotiated phase-out of nuclear power; all these goals were realised by 2001 (Staiss, 2003). By January 1999, the 100.000 roofs programme (for about 350 MW) was started, providing subsidies in the form of low interest loans to investors. For the sake of speed, the programme did not take the form of a law but of a decree enacted by the Ministry of Economic Affairs. This ministry maximised bureaucratic obstacles at first, but relented after strong protests by parliamentary groups of the coalition (Witt, 1999b and 1999c). In 1999 3.500 such loans were granted for installations amounting to a mere 9 MW$_p$. It was clear that everyone was waiting for a revision of the Feed-in Law, which however took some time to prepare.

Later in 1999, the reform of the Feed-in Law was started. After launching the trial balloon of a renewable energy levy that the utilities would be able to institute voluntarily (Witt, 1999a), the Minister of Economic Affairs – in charge of this subject-matter – leaned in favour of a quota system. When it became clear that the minister was not prepared to respect agreements with the parliamentary party groups of the coalition, these groups seized the initiative and submitted a members' bill which the ministry then tried to dilute and delay without much success, and which was finally adopted as the Renewable Energy Sources Act in March 2000 (Mez, 2003a).

The deputies, particularly the Greens, were inspired by the local feed-in laws for solar power and wanted to move this approach to the federal level. For that purpose they organised a process involving a very large, partly technology-specific advocacy coalition – various environmental groups, the two solar industry associations, the association of the machinery and equipment producers VDMA, the metalworkers trade union IG Metall, three solar cell producers and politicians from some *Länder*, e.g. North Rhine-Westphalia (Pfeiffer, 2001). The unorthodox coalition even included a major utility (Preussen Elektra, which testified in favour of the new mechanism equalising the burden of the law on the national level although overall it would have preferred a quota system); as a result the big utilities were not united in their opposition. From these organisations and individuals, the Greens received help in terms of both information and support in influencing members of parliament.

The Social Democrats for their part had a strong industrial policy interest in re-writing the Feed-in Law (Eichert, 2001). They feared that the 1998 liberalisation of the energy market would lead to a long-term decline in employment in the energy sector and in the associated capital goods industry, which has always been a point of strength of German industry. At this time, the German wind turbine industry had grown to be the second largest in the world and exhibited great dynamism (Bergek and Jacobsson, 2003). With liberalisation, the price of electricity dropped, and with it, the remuneration for wind turbine owners. It was then feared that the incentive for further diffusion would be lost and that a less dynamic home market would hurt the German wind turbine industry. Strong renewables legislation, these deputies argued, would put German industrial structure and employment on a more sustainable basis both environmentally and economically.

While the Federation of German Industries strongly opposed the law, key industrial association VDMA (Equipment and Machinery Producers, counting about 3000 member firms with approximately one million employees) joined the ranks of its supporters – again demonstrating the increasingly broad legitimacy of renewables. The opposition parties (conservative CDU/CSU and the Liberals) were internally divided on many issues and unable to come up with a coherent alternative, though on the whole they argued for more competition and sometimes for state subsidies instead of passing on costs to final customers (Bechberger, 2000; Deutscher Bundestag, 2000a and 2000b). They also argued that the new law was bound to draw a state aid challenge from DG Competition, a point echoed by the Ministry of Economic Affairs. In fact, a special effort was made by the red-green members of parliament to ward off this possibility (rates declining over time; exclusion of state-owned utilities from the beneficiaries). After adoption of the law, DG Competition questioned its compatibility with EU rules; it withdrew its objection only in May 2002, even though the European Court in March 2001 had rejected a similar challenge in the case of *PreussenElektra v. Schleswag* (Lauber, 2001).

The Renewable Energy Sources Act repeated the Feed-in Law's commitment to take external costs into account. In fact, it provided three reasons for the special feed-in rates. First, it referred to the polluter pays principle with regard to external costs. The explanatory memorandum attached to the law explains that

> most of the social and ecological follow-up costs associated with conventional electricity generation are currently not borne by the operators of such installations but by the general public, the taxpayers and future generations. The Renewable Energy Sources Act merely reduces this competitive advantage...

Second, the memorandum stresses that "conventional energy sources still benefit from substantial government subsidies which keep their prices artificially low". Third, the act purports to break the vicious circle of high unit costs and low production volumes typical of technologies for the generation of renewables sourced electricity (Federal Ministry of the Environment, 2000).

Under the new law, the rates of the tariff scheme were guaranteed to investors for 20 years (under the old Feed-in Law no such guarantee had existed). With regard to wind, rates varied with site quality. For at least five years from an installation date in 2000 or 2001 (nine years for offshore), the rate was to amount to €0.091/kWh, and longer depending on how far a turbine remained below the performance of a reference facility. For the first years of operation this meant an improvement of more than 10 per cent over the rate applicable under the previous system in 1998 and 1999 (Hirschl et al., 2002). This was compensated to various degrees by the later decline to €0.062/kWh. For turbines installed in 2002, these rates would be about 1.5 per cent lower, with the decline continuing at that annual rate (always for new installations only) for subsequent years, reinforced by inflation since rates are not adjusted to take it into account (Staiss, 2003). Overall this meant greater security for investors, particularly due to the 20-year guarantee mentioned above (Bönning, 2000). As a result, the diffusion of wind turbines was greatly stimulated (see figure 3).

With regard to solar, the improvement in incentives was much more dramatic. For 2000 and 2001, the new rates amounted to €0.506/kWh for solar cell facilities mounted on buildings, with a size of up to 5 MW$_p$, and for other facilities up to 100 kWp. This rate was guaranteed until a cumulative capacity of 350 MW$_p$ was reached. All this would probably not have been obtained without the very considerable interest in paying for solar electricity as revealed by the numerous local feed-in laws (Scheer, 2001) as well as by survey data (Solarenergie-Förderverein, 1996). Here too the rate of compensation was set to decline every year for new installations, so that a solar cell unit installed in 2003 would receive €0.457/kWh for 20 years. The annual decline was to be about five per cent (Staiss, 2002).

In combination with the 100.000 roofs programme, the revised feed-in-law meant that solar cells became an interesting investment option for the first time. As is evident in figure 4, diffusion took off. A booming market attracted additional entrants that enlarged the industry further.[22] For instance, in 2000, there were ten firms showing roof integrated solar cells at an exhibition (Neuner, 2001), and Germany is seen as the world leader in roof integrated solar cells (Maycock, 2000). Also, the number of solar cell manufacturers rose from two in 1996 to six in 2000 and, as importantly, ASE announced that it would increase its capacity from 20 to 80 MW (Schmela, 2001).[23] In the end, it raised capacity to 50 MW by the end of 2002 (under the name of RWE-Schott Solar).

Within less than three years – in mid-2003 – the 350 MW$_p$ ceiling was reached (150 MW were allocated just in the first six months of 2003 under the 100.000 roof programme; with this the programme ran out). Even though the ceiling for solar cell installations receiving the special Renewable Energy Sources Act rates was raised in 2002 to the figure of 1.000 MW$_p$, investment decisions slowed down greatly in the second half of 2003 as these rates proved insufficient without the low-cost loans of the 100.000 roofs programme. By that time, another amendment to the Renewable Energy Sources Act, to be adopted some time in 2004, was on its way. To secure the continuous growth of the photovoltaics industry, an advance law – a stopgap measure passed in anticipation of a more thorough reform – was adopted by parliament just before 2003 ran out.

The Federation of German Industry (BDI) criticised the Renewable Energy Sources Act 2000 for creating exorbitant burdens, damaging German competitiveness and driving up electricity prices; the Utilities Association (VDEW) pointed to extra costs resulting from the law to justify considerable price increases to final customers, increases which more likely resulted from a decline of competition. Nonetheless pressure on renewables built up. amplified by the Ministry of Economic Affairs. Yet at the same time that ministry lost ground in terms of control over this policy area. In the parliamentary elections of 2002, the Greens had improved their support while the Social Democrats had declined; thus the Greens could claim a stronger position in government, and effectively secured the transfer of the competency for renewable energy from the Ministry of Economic Affairs (held by the social democrats) to the Environment Ministry (held by a Green). This also meant a shift in the parliamentary committee dealing with renewable energy, from the economic affairs committee to the environment committee.

Although no longer in charge of this policy matter, Economic Affairs minister Wolfgang Clement from coal state North Rhine Westphalia joined the critics of the Renewable Energy Sources Act, and in summer 2003 a hardship clause was adopted supposedly to reduce the burden for those firms which could prove that their competitive standing was seriously affected. Only 40 firms were able to successfully invoke that clause by the end of 2003 (Witt, 2003; *Windpower Monthly* 19:9, Sept. 2003, 26; Deutscher Bundestag, 2004). Usually the utilities supplying industrial customers – for whom competition is intense – shift the burden to household and small business clients, whose burden is increased as a result (Bröer, 2003).

By summer/fall 2003, Clement also questioned the very principle of feed-in tariffs, apparently with the motive to secure a package deal for the protection of coal interests. Some Conservative and Liberal leaders – in particular conservative leader Angela Merkel – also attacked the Renewable Energy Sources Act because its "subsidies" supposedly represent a burden for the budget (when in fact, since they are paid for by consumers, they do not even show up there). Coal and nuclear interests are thus fighting the law with new vigour – probably because there is now a real possibility that they might be displaced, with no growth expected in electricity demand, over the coming decades with renewable energy. Undoubtedly they also view the ratification crisis of the Kyoto protocol (after Bush's rejection) as an opportunity to question the whole Kyoto philosophy. become more confident due to Bush's rejection of the Kyoto protocol. However, German public opinion seems still strongly committed to climate policy and renewable energy (Brechin, 2003; Solarenergie-Förderverein, 2003). More importantly perhaps, the conflicts over the Renewable Energy Sources Act in 2003 produced two new members of the renewables coalition: the German Confederation of Small and Medium-Sized Enterprises (BVMW) – representing about two thirds of all employment – and service workers union ver.di.

In sum, the red-green coalition which came to power in 1998 not only adopted the 'old' proposal of 100.000 roofs programme early on but, drawing on broad and increasingly strong advocacy coalition which now included VDMA, it also rewrote the Feed-in Law in a manner which was advantageous to wind and solar power. The diffusion of wind turbines took off again and that of solar cells soared. A clear feed- back loop from early diffusion to subsequent ability to influence the political process shaping the regulatory framework can be discerned. Yet, the very success of that framework led to an intensified efforts of coal and nuclear interest to change it – the 'battle' over the nature of institutions now moves into its third decade.

4. Financial flows and social costs: orders of magnitude

The current renewable energy policy must be seen in a wider context. For the Conservative-Liberal government, renewable energy was "complementary" energy rather than an alternative. For most of the red-green coalition, it is imperative that these energy sources replace other sources in the course of the 21st century. This is part of a climate strategy, which in 2020 should reduce CO_2 emissions by about 40 per cent, and by 80 per cent in 2050 (Jänicke, 2002; Bundesministerium für Umwelt, 2003). As repeated in April 2003, the current German government – though somewhat divided on the issue – and especially its parliamentary party groups want renewables sourced electricity to grow, from 6.25 per cent in 2000, to 12.5 per cent in 2010. By 2050, renewable energy (including imports) is envisioned to contribute above 60 per cent of total electricity demand (Bundesregierung 2002a; Bundesregierung 2002b). In this scenario, electricity from renewable energy sources is expected to require regulatory support until about 2020. After 2030 or 2035, it is expected to become cheaper than conventional generation, with a payback date some time before 2050 (Nitsch, 2002).

These visions, emanating mostly from the environment ministry, have led to important controversies. Not surprisingly, the Ministry of Economic Affairs – traditionally the advocate of conventional energy sources – arrives at cost estimates for an energy transition to renewables which are up to ten times higher, though most of these costs are seen to occur in the transportation sector (Fischedick et al., 2002). Criticism also comes from parts of the Conservative-Liberal opposition[24]. It is interesting therefore to look at the financial flows as well as the social costs connected with the different form of electricity generation. We will argue that the social (i.e., society's) price tag for conventional power generation is much higher than the private (i.e. the consumers electricity bills); that the support given to renewables is but a fraction of that given to 'conventional technologies' and, finally, that the remuneration under current support policy is broadly equal to avoided social costs and, therefore, involves no or very small extra costs for society.

The social cost of power generation based on coal is much higher than the private. In calculating social costs, we need to consider both subsidies and external costs. In terms of 2003 Euros, *subsidies* to hard coal for electricity generation can be estimated very roughly at about €80-100 billion for the period 1975-2002[25]; another 16 billion are scheduled for the period 2005-2012 (Bundesverfassungsgericht 1994; Wachendorf, 1994; IEA, 2002; *Solarzeitalter* 4/2003, 57)). During the same time period, hard coal and lignite together caused *external costs* in the range of €400 billion or more, probably substantially more as external costs were considerable higher before the widespread use of flue gas cleaning (European Commission, 2003).[26] Total government funded R&D for coal amounts to €2.9 billion for 1974-2002 (IEA, 2003a).

Nuclear fission in Germany cost taxpayers some €14 billion in R&D funds since 1974 (IEA, 2003a; see also figure 5). This amount was spent "to establish an internationally competitive industry", a goal which in the view of the government was not to be hindered by "a premature and overstressed bias towards economic aspects" on the part of the utilities. It is true that most of these funds went to the development of "advanced reactors" such as the high-temperature gas-cooled reactor or the fast breeder reactor (Keck, 1980, 316). However, at that time it was thought that advanced reactors relying on plutonium represented the future of nuclear power, since the uranium used in light water reactors would sooner or later become scarce (Meyer-Abich and Schefold, 1986). For the purposes of the advanced reactor programme, the concept of "R&D" was interpreted quite generously; "in order to facilitate financial support by the Federal Government, the programme was framed as an experimental development programme rather than a programme aimed at early commercialization" (Keck, 1980, 323).[27] Finally, participation in the international nuclear fusion programme so far caused Germany R&D expenses of slightly more than €3 billion (IEA 2003a), but this contribution will have to be multiplied many times over before fusion may actually generate electricity, estimated to occur not before 2050.

How does wind and photovoltaic power compare to all this? From 1975 through 2002, in terms of government R&D funds, wind received €0.47 billion, and solar cells €1.15billion (IEA, 2003a; Sandtner et al.,1997; Räuber, 2002; Deutscher Bundestag, 2003; see also fig. 5). The red-green coalition so far has not modified energy research priorities substantially, even though Scheer and Fell – the parliamentary leaders of the coalition parties on renewable energy sources – are asking for an increase of R&D on those sources by a factor of ten (Eurosolar, 2003a; Frey, 2003; Siemer, 2003). There is also a cost resulting form market creation programmes. The 250 MW wind programme caused cumulative costs of €0.15 billion from 1989 through 2001 (Staiss, 2003, II-27); to this the costs of the *Länder* programmes must here be added, e.g. of Schleswig-Holstein and Lower Saxony (Paul, 2003). Most expensive so far is the 100.000 roofs programme; its cost was estimated at €0.1 billion for 2001 only (Fischedick et al., 2002). Although this cost varies according to the prevailing interest rates (Genennig, 2002), it is safe to assume that annual cost in future is likely to be several times this amount, for a period of almost 20 years. Yet, we are speaking in terms of very small figures in the context of the energy sector. As to external costs, they were estimated in the ExternE study to amount to 0.05 Eurocents for wind power and to 0.6 Eurocents for solar PV[28] (European Commission, 2003).

The largest flow of funds connected to renewables is in connection with compensation under the Renewable Energy Sources Act. In 2002, this amounted to €2.2 billion (Deutscher Bundestag, 2003) for 24 TWh (*Umwelt* 5/2003, 589), which means an average feed-in rate of 9.1 Eurocents per kW$_h$. Compensation under this act will certainly grow for some time, and a 50 per cent increase of total compensation under the Renewable Energy Sources Act is expected between 2002 and 2005 (Deutscher Bundestag, 2003).

The difference between this compensation and that of the private cost of conventional power generation was about €1.45 billion in 2002. However, the relevant measure to consider is the social cost of that power. In other words, we need to relate the compensation under the Renewable Energy Sources Act to the social cost of generation power with conventional, coal based technologies. For 2002, the cost of electricity generated from hard coal can be estimated at 9.9 to 12.5 Eurocents/kWh. This includes 3.4 to 3.8 cents direct generation costs (Staiss 2003, I-248), 2 to 4.2 cents from coal subsidies (estimated on the basis of IEA, 2002; Statistik der Kohlenwirtschaft, 2003; for the higher figure see Janzing, 2004) and 4.5 cents[29] in external costs (European Commission, 2003). For electricity from soft coal, the respective figure is 7.9 to 8.3 cents.[30] The 9.1 cents resulting from the Renewable Energy Sources Act mix of tariffs (see preceding paragraph), augmented by slightly more than 0.05 cents of external costs, are in between hard and soft coal generated electricity. As to wind power from turbines installed in 2002, the average rate over the 20 year period is somewhere near 7.5 cents including external costs (9 cents for the first five years or longer, coming down to 6.1 cents afterwards). There are two implications of this. First, if social costs are taken seriously – and this was one of the declared goals of both the Feed-in Law and of the Renewable Energy Sources Act – most renewables sourced electricity (though not solar cells) would be in the competitive range right now. Second, the remuneration under this act roughly equals the avoided social costs of coal-generated electricity, which means that in social terms, the extra cost to society appears to be negligible.

In short, taking into account all costs including subsidies and external costs, to increase the share of electricity covered by the Renewable Energy Sources Act appears as a well-founded choice for German society to take even in financial terms. And there are additional considerations in favour of such a choice. Security of supply is one of them. Being a technology leader also confers "early mover" advantages, and the advocates of the German climate strategy view renewables sourced electricity as an area of strong export potential. Already renewable energy sources have created about 120.000 to 150.000 jobs; a further increase can be expected in the future. Also, the annual private cost per capita – about €18 in 2002 – seems far from exorbitant.[31]

5. Conclusions

It might come as a surprise to see Germany among the leaders in the transformation of the energy system (here with regard to electricity). In the twentieth century, Germany was one of the few large industrial states without oil resources and no large oil corporation of its own (Karlsch and Stokes, 2003). Partly for this reason, it came to rely with particular intensity on domestic coal, and later on nuclear energy. This was reinforced by the energy crises of the 1970s, where such a choice was imposed in a rather authoritarian fashion by chancellor Helmut Schmidt, and was continued by his successor Helmut Kohl after 1982. But then, this choice led to intense controversies and the rise of a strong anti-nuclear movement in the 1970s, a strong environmental movement in the 1980s (especially over acid rain, largely from coal) and the first big Green party in Europe. Early on, renewable energy sources caught public attention as an alternative to the nuclear path towards a plutonium economy. Under pressure from a movement in favour of renewables, the above governments with some reluctance also supported the development of renewable energy sources, though not for domestic use at first.

Even this limited and ambivalent support fell on fertile ground, as there was a broad range of people just waiting to play an active role in developing the new technologies – as researchers, farmers, technicians, entrepreneurs, customers etc. For this reason even modest support was enough to create a space for wind and solar power to start out on a formative period. All four features of such periods were present: institutional change in the form of a changed energy R&D policy (although only on the margin), the formation of markets (although very small) in the form of protected niches, entry of firms and establishment of some of the elements of an advocacy coalition. Hence, all the four features were there, if only in an embryonic form while the existing structure remained intact. Yet, the value of this very first phase did not lie in the rate at which the new technology was diffused, or whether or not existing structures (e.g. regulatory regime) were altered, but in the opportunities for experimentation, learning and the formation of visions of a future where renewables would play a prominent role in electricity generation.

In the second half of the 1980s, Chernobyl, forest die-back due to acid rain and the emergence of climate change as a political issue led to strong demands for change from the public. These demands were mediated creatively not by the government, but by the parliamentary groups of the political parties who on these issues were unusually co-operative. They also learned to pressure and if necessary to bypass the government; in that sense Germany - like Denmark from the early 1980s to the early 1990s (Andersen, 1997) - also had its "green majority" in parliament prepared to bypass governments which were considerably less "green", except that in the German case this majority, although somewhat thinned by now, has held up for a decade and a half so far.

These demands led to the first important measures of market formation in the late 1980s. Large-scale demonstration programmes were initiated (250 MW and 1,000 roofs) which involved a very significant upscaling of the initial protected market space. The 1990 Feed-in Law gave additional and powerful financial incentives to investors in renewables. A first feed-back loop from the investments in the formative phase to an emerging advocacy coalition capable of influencing the institutional framework can here be discerned. Indeed, with hindsight, the Feed-in-Law may well be seen as the first sign of a breach into an old structure.

With such a dramatic change in the institutional framework, wind power was able to move into a take-off phase characterised by very rapid diffusion.[32] Firms were induced to enter into the buoyant industry, learning networks evolved and the advocacy coalition was strengthened. Thus, virtuous circles, which involved all the four features, began to operate. The 'unimaginable' growth also led to an adjustment in beliefs. While Liberals and most Conservatives continued to see renewables as a 'complementary' source of energy, the parliamentary group of SPD developed visions of a transition to renewables which came close to that of the Greens. The legitimacy of renewables gained additional strength in the political arena.

When the established actor network (utilities with the help of the Ministry of Economic Affairs DG Competition) attempted a rollback of the Feed-in Law in the mid-1990s, they met with opposition from a coalition which had been strengthened by a rapid diffusion of wind turbines and was powerful enough to maintain regulatory continuity – one of the key criteria of success in this area (Haas et al., 2004). Thus, the advocacy coalition had gained enough strength to win battles over the shape of the regulatory framework – a second feed-back loop from diffusion to the process of policy making is here highly visible.[33]

Meanwhile, for solar power, a set of local initiatives provided enough protected market spaces for the industry to survive. Although small, these markets induced further entry of firms and revealed a strong legitimacy for solar power, which later helped the Greens and SPD to alter the regulatory framework to the benefit of solar power.

When the red-green coalition took over in 1998, its parliamentary party groups – once more against the opposition of the Ministry of Economic Affairs – soon took measures to vastly increase the protected market space for solar power (100,000 roofs), to further improve the conditions for investors in wind power (in particular by further reducing uncertainty) and to give investors in solar cells adequate financial incentives. In order to achieve this, the coalition drew in yet new actors into this policy network, coming partly from the renewable energy sector (equipment producers, owners and operators of installations and their associations), partly from "conventional" associations such as investment goods industry association VDMA or the metalworkers union, which had joined the coalition during the preceding years.

This institutional change accelerated wind power installation and brought an early take-off phase for solar cells as well. A virtuous circle was set in motion for solar power where the enlarged market induced yet more firms to enter and strengthened the coalition further. Indeed, in 2003/2004, the coalition – supplemented by new allies such as the union of service workers and the confederation of small and medium sized enterprises (Eurosolar, 2003b) – is trying to repeat this feat against a renewed opposition from the nuclear and coal interests. In this, they may well be successful, as the new regulatory regime has gained widespread support. The revision of the Feed-in law in 2000 was even supported by one of the largest utilities and in late 2003, CDU/CSU members of parliament supported the advance law for solar cells.

This suggests not only a wider acceptance of the regulatory regime but also that these CDU/CSU members may now share a vision where solar cells will have a substantial role to play within a few decades. Legitimacy of a new technology and visions of its role in the future electricity generation is therefore not only a prerequisite for the initiation of a development and diffusion process but also a result of that very same process. Legitimacy and visions are shaped in a process of cumulative causation where institutional change, market formation, entry of firms (and other organisations) and the formation and strengthening of advocacy coalitions are the constituent parts. At the heart of that process lies the battle over the regulatory framework.

However, to be successful, the diffusion must be defensible also on economic grounds. The comparison with other available sources shows that in terms of overall cost to society, renewables sourced electricity is likely to be a perfectly reasonable choice, and one that will be amortised within a time span that is not unusual for major infrastructure investments. It is clearly somewhat ironic that a major political struggle was required merely to 'get prices right' (and to get away from an inferior choice of technology from a social perspective) often against an opposition which appears to be playing that very same tune. Even so, and despite the exceptionally high degree of legitimacy of renewable energy sources in German society, it may be difficult to maintain a supportive policy for the time period required, i.e. another two decades, against established actors which are still well-connected, particularly in a policy environment marked by liberalisation and privileging considerations of short term profitability over long-term strategies. Perhaps successful exports of the wind and photovoltaics industry will contribute a momentum of their own. But as the Danish turnaround on renewable energy after the 2001 elections shows, such processes of diffusion are not deterministic but unpredictable, not only carefully orchestrated but also influenced by many chance events.

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[1] This paper is a joint product of the two authors. The input made by Jacobsson comes from a large project pursued together with Anna Bergek, Lennart Bångens and Björn Sandén

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(formerly Andersson). Jacobsson's input thus draws extensively from three of the papers written in that project. Key references are Bergek and Jacobsson (2003), Jacobsson and Bergek (2003) and Jacobsson et al. (2002). We are grateful to these three colleagues as well as to two anonymous referees and the Editor, who gave valuable comments on an early draft.

[2] The section draws a great deal on Jacobsson and Bergek (2003).

[3] This data is for 1998.

[4] Whereas we focus on these two technologies, we are aware of a larger range of renewables that include e.g. wave power, new ways of using biomass (e.g. gasified biomass – see Bergek, 2002) and thermal heating.

[5] Already in the 1930s, experiments with large (several hundred kW) wind turbines for electricity generation were undertaken Germany, and the first solar cell was produced in 1954 by the Bell laboratories (Heymann, 1995; Wolf, 1974, cited in Jacobsson et al., 2002)

[6] For reasons of space limitations, the discussion has had to be held brief. A longer discussion is found in Jacobsson and Bergek (2003) and in Carlsson and Jacobsson (2004).

[7] Committee of the Bundestag (lower house) composed half of MPs, half of experts who also have the right to vote. Enquete commissions are set up irregularly to deal with major new policy issues turning very substantially on scientific expertise.

[8] Conservative is used as synonymous with Christian Democratic

[9] Only some local utilities – Stadtwerke, i.e. municipal utilities – took a different course.

[10] The numbers exclude funding given for the purpose of demonstration wind turbines. In addition, there was support for projects that could benefit all sizes of turbines.

[11] These are estimates based on elaboration of data from Jahresbericht Energieforschung und Energietechnologien, various issues, Bundesministerium für Wirtschaft und Technologie.

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[12] These were: amorphous silicon (aSi), copper sulphide, cadmium selenide, cadmium telluride and copper indium diselenide (CIS).

[13] According to Hemmelskamp (1998), 214 turbines were supported.

[14] In addition, private operators, e.g. farmers, had the possibility to obtain an investment subsidy (Durstewitz, 2000a).

[15] In the early 1990s, the Ministry of Economic Affairs actually demanded a very large support programme for renewable energies (about €0,7 5billion) but could not secure the necessary political support (Hemmelskamp 1999).

[16] Generators were not required to negotiate contracts, participate in bidding procedures or obtain complicated permits; this simplicity was certainly essential for the success of this act (von Fabeck, 1998).

[17] This was the word used by a central person in the evolution of the German wind turbine industry and market.

[18] The bulk of the sales within the 100/250 MW programme took place 1990-1995 and the programme accounted for most of the nearly 60 MW that were installed in the years 1990-1992 (ISET, 1999, table 3).

[19] In 1994, the Kohlenpfenning was held unconstitutional (Bundesverfassungsgericht 1994; Wachendorf, 1994).

[20] In the same year, Bayernwerk introduced the first 'green pricing' scheme, which involved investment in a 50 kW_p plant. Shares were sold to about 100 people who paid about DM 0.2 – about 1 Eurocent – per kWh (Schiebelsberger, 2001). Many such schemes followed, for instance by RWE in 1996. About 15 000 subscribers eventually paid an eco-tariff (twice the normal tariff) for electricity generated by solar cells, hydropower and wind (Mades, 2001).

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[21] The late 1980s and the 1990s saw a veritable proliferation of renewable energy associations. For instance, an association for biogas (1992), one for biomass (1998) and yet another solar energy association (UVS, 1998). Most of these engage in lobbying and educational activities, sometimes also in exchange of information and experience.

[22] Some firms also entered a few years earlier in response to the market formation following the local feed-in laws.

[23] In 1998, domestic module production had covered less than one quarter of a domestic demand of 12 MW. Beginning in 1999 (demand 15 MW, production 4.3 MW), these figures increased steeply: 40 per cent of a demand of 66.5 MW was covered in 2001. Estimates stand at around 70 per cent for 2002 and 2003. A survey of the industry carried out in 2003 listed four wafer manufacturers, eight cell producers and twenty-one manufacturers of modules, some of them highly specialised (Hirschl et al., 2002; *Solarthemen* 170, 23 Oct 2003, 1).

[24] In early 2004, CDU/CSU MPs were willing to support the government amendment to the Renewable Energy Sources Act on condition that a ceiling be introduced to limit feed-in payments in total volume, not in terms of extra cost; this ceiling is likely to be reached by 2010 or earlier (*Solarthemen* 176, 29.1.2004, 2).

[25] The actual figures may be higher as these figures do not seem to be adjusted for inflation

[26] A tax exemption for coal-generated electricity also needs to be mentioned here.

[27] Tax breaks on undistributed profits for power plant decommissioning cost another €18 billion by 1998 (Mez, 2003b), and more since then. Extra costs to electricity consumers resulting from defective nuclear technology or simply expensive entrepreneurial decisions in this context were usually hidden in the electric rates allowed by sympathetic regulators in the days of territorial monopolies with privileged political connections (before 1998) and are

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therefore harder to identify (Mez and Piening, 1999). For the sake of perspective, it should also be added that total research spending on nuclear energy in OECD countries is estimated at about €150 billion, supplemented by about €300 billion in cross-subsidies from electricity tariffs, not counting damages or the cost of returning nuclear sites to their former state (Rechsteiner, 2003). There is also low insurance coverage for nuclear accidents.

[28] The figures for solar PV in Germany are about ten years old and therefore problematic (Nickel, 2004).

[29] This figure is in the middle of a range 3-6 cents.

[30] These figures will go up as old coal plants need to be replaced, whereas the cost of generation per kWh of renewables sourced electricity will decline from now on if – as intended – solar cells will be introduced at a moderate rhythm.

[31] As to a more rapid introduction of competitive mechanisms, their impact in Europe is quite limited so far (Lauber, 2004) and does not always point into the direction expected. Thus, prices for wind power seem to be considerably higher at present under Britain's renewable obligation system than in Germany, despite a more "competitive" mechanism and much better wind conditions (Knight, 2003).

[32] Those measures were well designed in terms of regulatory design and impact, in particular the Feed-in Law. Bureaucratic entanglements and complex procedures were largely avoided.

[33] Whereas Denmark in 1999 gave in under EU pressure and accepted liberalisation of renewables sourced electricity as unavoidable, the German parliament stuck to its guns.

ATTACHMENT 10

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Regime Shifts to Sustainability Through Processes of Niche Formation: The Approach of Strategic Niche Management

RENÉ KEMP, JOHAN SCHOT & REMCO HOOGMA

ABSTRACT *The unsustainability of the present trajectories of technical change in sectors such as transport and agriculture is widely recognized. It is far from clear, however, how a transition to more sustainable modes of development may be achieved. Sustainable technologies that fulfil important user requirements in terms of performance and price are most often not available on the market. Ideas of what might be more sustainable technologies exist, but the long development times, uncertainty about market demand and social gains, and the need for change at different levels—in organization, technology, infrastructure and the wider social and institutional context—provide a great barrier. This raises the question of how the potential of more sustainable technologies and modes of development may be exploited. In this article we describe how technical change is locked into dominant technological regimes, and present a perspective, called strategic niche management, on how to expedite a transition into a new regime. The perspective consists of the creation and/or management of niches for promising technologies.*

Introduction[1]

Every new car show features the glorious introduction of environmentally benign vehicles. Examples are electric vehicles powered by batteries, hybrid-electric vehicles with small petrol or diesel engines generating electricity on-board, natural gas vehicles, lightweight vehicles built with composite materials instead of metal and vehicles for public individual transport systems.[2] Only very few of the vehicles are for sale. This raises the question of why such technologies are not introduced into the market-place when their benefits to society are so evident. Is there no market for these technologies? This is what the automobile manufacturers tell us. But why is there no market? Is it because consumers do not want to pay extra for environmental benefits? Or are the reasons political, namely the failure of policy-makers to make environmental benefits an integral part of the structure of incentives and constraints in which people trade and interact? Or is it that manufacturers think that there is no market or find the market for environmentally desirable automobiles less attractive than the market for gasoline automobiles? As we will argue, there is not just one barrier to the introduction of alternative vehicles but a whole range of factors that work against the introduction and diffusion of alternative

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vehicles. The slow diffusion of environmentally preferable technologies is by no means exceptional, although there are extra barriers for clean vehicles.[3]

In the innovation literature, the hard times for new technologies are a common theme. To develop a new idea into a prototype and product means overcoming resistance both outside and inside the innovating organization. It requires a special kind of management: the management of attention, of riding ideas into currency, of managing part–whole relationships (integrating functions, organizational units and resources) and the institutionalization of leadership.[4] In the organization, new innovations often receive lukewarm support. Most innovations do not start out as a strategic activity but as a peripheral activity of a small team of developers, as most of the research and development (R&D) work in the organization is geared towards improving existing products and reducing their production costs. This holds particularly true for automobile development. After an initial period of competing designs in drive trains (roughly 1890–1920), a dominant design emerged which is still the basic design in automobile development. This basic design consists of an internal combustion engine, a metal body and a steering wheel, to name a few salient features. Although the automobile industry is quite innovative, when it comes to increasing vehicle performance, safety and comfort, often by the application of electronics, the basic design is maintained. As to the functional and manufacturing characteristics, most vehicles are multi-purpose vehicles that are produced in highly standardized processes, even though automobile producers have shifted to more flexible modes of production. In the past decade, the model range has been extended, with the very successful minivans (six to eight passenger vans on a car platform) and 'recreational vehicles' or sports utility vehicles (Jeep and pick-up lookalikes), as well as the thus far less successful urban cars (small two-seaters). Although different in their appearance, they do not constitute a departure from the basic design. A possible exception is electric versions of urban cars, for which a small niche market exists in a few countries. The innovations just outlined have generally not been positive from an environmental point of view. Engines have become cleaner and more efficient in the past decade and a half, but added safety features and other accessories and consumer preferences for bigger cars have meanwhile resulted in higher average fuel consumption of cars. The successful minivans and sports utility vehicles, especially, are 'gas-guzzlers'.[5]

The idea of a basic or dominant design is an important notion in the innovation literature. It was introduced by Abernathy and Utterback in their study of technical change in the US automobile, aircraft and electronics industry. In each industry, a dominant design emerged which served as the basis of development work, both inside and outside the industry. It served as a model for development, by defining an outlook or frame of reference for engineers, and enabled standardization, so that production economies can be sought.[6] The idea of a technological framework and shared outlook of engineers was developed further by Nelson and Winter, and Dosi, Nelson and Winter use the notion of a technological regime and Dosi of a technological paradigm to account for the problem-solving activities of engineers.[7]

An important characteristic of the concepts of technological paradigm and technological regime is the existence of a core technological framework that is shared by a community of technological and economic actors as the starting point for looking for improvements in product and process efficiency. It focuses the attention of engineers upon certain problems, while neglecting others. As Dosi writes, "a technological paradigm has a powerful exclusion effect: the efforts and the technological imagination of engineers and of the organisations they are in are focused in rather precise directions while they are, so to speak, 'blind' with respect of other technological possibilities".[8] Although the authors are not very explicit about the causal factors leading to this exclusion effect, they suggest that two factors play a key role: first, the consensus of engineering beliefs and the shared knowledge about the key parameters and binding constraints;[9] second, beliefs as to what the market wants. Thus, unlike biological evolution, variations are not blind. Dosi speaks of *ex ante* selection.[10] This *ex ante* selection takes places when firms anticipate possible selection by the market and a wider set of institutional factors together comprising the selection environment. What is missing in these approaches, however, is an account of how changes in the economic and social environment impact on the research agenda of firms (and other technology actors) and how the selection environment is shaped by old technologies (through the emergence of production routines, existence of infrastructures, the formation of skills and habits, and established consumption patterns). In our view, engineering beliefs and approaches and *ex ante* selection are important elements in the direction of technological change, but as an explanation for the direction and nature of technical change they are incomplete because the issue of the coupling of variation and selection processes is insufficiently developed. In the following we will argue that variation and selection are linked to each other through what we will call a technological regime.[11]

In the next section, we take a closer look at the different factors that affect the development and use of new transport technologies, in particular how they impede a shift to more sustainable transport technologies. In doing so, we focus on the barriers for more sustainable transport technologies. These barriers are discussed individually, although it is the combined occurrence of the barriers that is responsible for the slow transition to more sustainable transport technologies. We then look at technology concepts from innovation theory to explain the slow transition, and offer a critical discussion of the concept of a technological paradigm. We advance the concept of a technological regime, which is used as a key concept in this paper. Then we examine the problem of technological regime shifts and discuss the ways in which technical change may be oriented towards social goals by public policy-makers. We point out the limitations of traditional technology promotion and control policies and the need to take a process approach to orient the dynamics of socio-technical change in socially beneficial directions. The final section describes strategic niche management as a way to manage the transition into another technological regime.

Why Is There Under-utilization of More Sustainable (Transport) Technologies?

Technological Factors[12]

One important barrier to the introduction and use of new technology is that the new technology does not fit well into the existing transportation system. The use of the new technology may require complementary technologies that are perhaps not available (in short supply) or expensive to use. The introduction of battery-fed electric vehicles, for example, will require the development of an infrastructure for charging batteries. It may also be that the technology itself needs to be further developed. In the early phase of their development, new technologies are often ill-developed in terms of user needs and expensive because of low-scale production. They need to be optimized. A related factor is that the new technologies have not yet been tested by consumers on a large scale. Actual large-scale use will lead to redesigning and new, unforeseen design specifications. These technological barriers have been given increased attention over the past couple of years, especially in connection with various experiments with new technologies (electric vehicles, natural gas vehicles, etc.) that are being carried out in various countries.

Government Policy and Regulatory Framework

Government policy may also be a barrier. Even though governments are committed to environmental protection and other social goals, they are often not putting out a clear message that there is a need for specific new technologies. In a sense the signals are conflicting because nearly all new technologies are stimulated by R&D subsidies, even though it is not clear which role they should play in a future transportation system. In none of the countries studied by Elzen *et al.* was there a technology policy based on a clear view of the future to guide technology developers, planners and investors towards sustainable development.[13] The manufacturers therefore remain uncertain about the market developments and will be reluctant to invest in precarious and risky alternatives. Moreover, the existing regulatory framework may actually form a barrier to the development of new technologies. For instance, the very strict safety requirements in the Japanese natural gas law drives up the price of on-board gas cylinders and refuelling stations to five times the level of other countries. The Californian zero-emission vehicle (ZEV) legislation has strongly stimulated the development of electric vehicles but discourages the development of hybrid-electric vehicles, although the latter may be cleaner if the emissions by electricity production plants are taken into account.[14] Adaptations of legislation are often quite cumbersome, partly because some of the actors may oppose them.

Cultural and Psychological Factors

There may also be cultural and psychological factor barriers. In this century, the automobile, with its high speed and the possibility it offers of freedom on the road at any given time, has become an icon of the modern life-style. Values such as flexibility and freedom are associated with the possession and use of a car. For many automobile users, owning and driving a car is a way of expressing their individual and societal identity: their car is an expression of status.

Car manufacturers, consumers and car salesmen have an idea of what a car is and should be able to do. This image may not accord with that of the different alternatives. The unfamiliarity with the alternatives often leads to scepticism beforehand, because the actors mentioned judge the new technology on the basis of the characteristics of the dominant technology. An example is the so-called idle-off device that has been offered by Volkswagen in some of its models. This device shuts off the engine when the car is stationary or slowing down. This may limit fuel consumption in the city by 20–30%, and also strongly reduce emissions. When the car accelerates the engine will restart automatically. The idle-off device has not been a success, because Volkswagen and the dealers do not dare to promote this option. They think that drivers will fear that the engine will not restart, and therefore prefer the certainty of hearing the engine run when stationary.

Demand Factors

There are economic barriers to do with prospective users' preferences, risk aversion and willingness to pay. The new technologies have not proven what they are worth, so consumers are not sure what to expect. The meaning and implications of the new technologies have yet to be specified by their application in practice. New technologies may also not meet the specific demands of consumers, which means that an alteration of these demands and preferences may be required to introduce the technologies. The battery-powered electric vehicle's limited range will force its user to adapt his/her travel patterns. Only a few consumers will accept a lesser performance of the product in return for a lesser environmental impact. The insecurities and aversions of the consumer are sufficient reason for the manufacturers of the new technologies not to market certain new products. This market is very sensitive, and a loss of market share because of the failed introduction of a new product may cause serious problems. The manufacturers of existing technologies prefer to avoid risks by building on current consumer preferences. Automobile dealers, who are supposed to sell the cars to the consumers, are reluctant to promote cars that do not meet traditional consumer preferences.

Another important demand factor is the price of the product. New technologies are often expensive owing to the small scale of production and because they have not benefited from dynamic learning economies on the supply side.[15] The high price that results from the high unit costs of production is quite a disadvantage in the automobile market, where all the major manufacturers compete on price. Even relatively simple new technologies (for example, the pre-heated catalyst[16]) have a hard time on account of their raising of the cost price.

The manufacturers think that consumer demands cannot be changed, and therefore they often refer to them as the most important barriers. Their argument is that they cannot manufacture products for which there is no clearly articulated consumer demand. However, the success story of the minivan in the US undermines this argument. As shown by Porac *et al.*,[17] consumer research in the late 1970s had indicated a widespread sentiment in favour of a small people mover van in the US. The American car manufacturers started development of such a van, but Ford concluded that the vehicle would become too costly and General Motors (GM) considered the market too fragmented. Only Chrysler went ahead in an all-or-nothing gamble in the face of bankruptcy, and hit instant success. Ford and GM then followed. The US minivan market currently comprises unit sales of over one million vehicles. This example does not directly compare to the assumed market for environmentally benign vehicles. The buyers of minivans did not have to settle for less with regard to comfort and performance, battery-powered electric vehicles have limited range and speed, and recharging the battery is very time-consuming.[18]

Production Factors

There are also barriers on the supply side. The development from prototype to mass product is quite a long and cumbersome process, but above all it is a risky process. There may be a chance to develop a new market, but the incentive for the automobile industry to introduce a product to the market is not high when it is far from certain that the consumer is interested in buying it, or when there are no external factors such as legislation that require automobile manufacturers to offer the product for sale to consumers. Investing in new technologies may mean that the sunk investments in existing production facilities will never be gained back. Moreover, existing companies do not want to risk their core competencies becoming superfluous. To the automobile industry, the mass production of cars with combustion engines is just such a core competence. Its organization is aligned to this competence, both technically (in terms of its products, production processes and R&D activities) and organizationally (in terms of modes of control, marketing and strategies). Generally, enterprises may aim their production strategies at: (1) cost leadership; offering products at the lowest price on the market; (2) differentiation, offering exclusive products (for example, of a specific brand) for a large market; or (3) producing for market niches, i.e. producing a limited assortment for a limited group of customers. The major car manufacturers predominantly choose strategy one or two; they have limited or no competence to produce cars for market niches. Therefore, the manufacturers are interested in alternative vehicles only when these can be produced for a big market.

In such a situation it often takes new enterprises to market the new products. These do not stand much of a chance, however, if they are not backed by sufficient capital. This creates an additional problem, since banks are reluctant to invest in risky projects and governments only grant subsidies for R&D and not for marketing a new product. Moreover, the new companies lack the competence to produce large quantities of cars of constant high quality. These factors constitute high barriers for newcomers. Cooperation between newcomers and the existing car industry might be able to change this. A good example is the cooperation between the Swiss company SMH and Mercedes, who intend to introduce a new type of vehicle to the market in 1998. Examples of small companies that have got into major financial problems are the Swedish company Clean Air Transport (CAT) and the American US Electricar. CAT missed an order for 10 000 hybrid vehicles (the prize in a competition organized by the city of Los Angeles) because Swedish financiers did not trust the company's competence. US Electricar was forced to give up the low-profit production of conversion-electric vehicles because of the decreasing value of its stocks. There are, however, more successful examples of new enterprises, such as the French SEER and German Hotzenblitz. For the moment, these companies produce on a small scale, however.

Infrastructure and Maintenance

The introduction of new technologies may require adaptation of the infrastructure. A new distribution system may have to be established, as for natural gas and hydrogen technology, or special provisions may have to be made; for example, for charging electric cars. Another adaptation concerns the maintenance that vehicles require. Mechanics in garages must get acquainted with the new technologies in order to be able to check and repair the new vehicles. A characteristic of infrastructure and maintenance investment is its threshold value: only with a relatively high number of vehicles does it become profitable to create a new infrastructure, although the vehicles require such an infrastructure from the very beginning. Crucial questions are, therefore, who is responsible for the development of the infrastructure and how the initial costs can be covered. Another problem is the so-called sunk investments in the existing infrastructure. The groups in charge of the current infrastructure form a strong lobby for their own interests.

Undesirable Societal and Environmental Effects of New Technologies

New technologies may be able to solve some problems, but they may also introduce new ones. The batteries of electric cars could cause an additional waste problem; some alternative fuels lead to an increase of certain types of emissions; growing crops required for the production of bio-fuels takes up a great deal of land, which prevents the use of that land for other purposes (growing alimentary crops or nature conservation, for example); the availability of cheap and very economic vehicles may cause a rebound effect in the form of an increase in vehicle mileage. Quite an effort will be required to find out if and how such problems can be solved. In the meantime, these problems affect the image and performance of the new technology.

Conclusion

As the foregoing discussion shows, there are many factors that impede the development and use of new technologies, especially systemic technologies that require changes in the outside world. These factors are interrelated and often reinforce each other. What we have is not a set of factors that act separately as a containment force, but a structure of interrelated factors that feed back upon one another, the combined influence of which gives rise to inertia and specific patterns in the direction of technological change. But what exactly is this structure and how does it affect technological choices of technology developers and users? These questions are examined in the next section.

The Structured Nature of Technological Change: Technological Regimes and Paradigms

The existence of patterns in technological change is widely recognized. Examples are miniaturization in microelectronic computers, the use of information technology in manufacturing and offices, the electrification of products and processes and so on. Economists, historians and sociologists have studied these regularities in technological change and have proposed concepts to account for the ordering and structuring of technology. We will describe two concepts that have been highly influential in social studies of technology: the concept of technological regime used by Nelson and Winter and Dosi's concept of technological paradigm.[19]

The concept of a technological regime was coined in the 1977 article 'In search of useful theory of innovation' by Nelson and Winter. In this article, they noted that the problem-solving activities of engineers were not fine-tuned to changes in cost and demand conditions, but relatively stable, focused on particular problems and informed by certain notions of how these problems could be dealt with. Nelson and Winter give the example of the DC3 aircraft in the 1930s, which defined a particular technological regime: metal skin, low wing, piston powered planes. As they write: "Engineers had some strong notions regarding the potential of this regime. For more than two decades innovation in aircraft design essentially involved better exploitation of this potential; improving the engines, enlarging the planes, making them more efficient."[20] Dosi speaks of a technological paradigm, analogous to Kuhn's concept of scientific paradigm. A technological paradigm consists of an exemplar—an artefact that is to be developed and improved—and a set of (search) heuristics, or engineering approaches, based on technicians' ideas and beliefs about where to go, what problems to solve and what sort of knowledge to draw on.

The idea of a core technological framework for industries guiding research activities has gained wide recognition in modern innovation theory. An advantage of this approach is its connection with existing engineering ideas and approaches, which the economic notion of production function fails to make. But as an approach to explain socio-technical change it is too limited, because it focuses too much on cognitive aspects of problem-solving activities and too little on the interplay between cognitive and economic and other social factors that force technological problem-solving in certain directions. This interplay must be perceived as a quasi-evolutionary process of variation and selection, in which the external selection pressures are anticipated by the innovator organization and incorporated into company R&D and production policies; the external selection environment in turn is shaped by the policies of the innovator vendor and a host of other actors who strive to promote (and control) a particular technology.[21] Engineering activities are embedded in larger technological regimes, which consist not only of a set of opportunities but also of a structure of constraints in the form of established practices, supplier–user relationships and consumption patterns. The choice for the internal combustion engine thus depends not just on the prevailing interpretative framework of engineers, but also on the embedding of the combustion engine in engineering practices, production plants and organizational routines, and the embedding of automobiles with internal combustion engines in fuel distribution systems, travel and mobility patterns and automobile repair and maintenance practices.

If we take the quasi-evolutionary dynamics of technical change as a starting point, we need a broader definition of technological regime. A technological regime needs to encompass both the paradigmatic framework of engineers and the selection environment of a technology. The definition of technological regime we use is:[22] "the whole complex of scientific knowledges, engineering practices, production process technologies, product characteristics, skills and procedures, and institutions and infrastructures that make up the totality of a technology". A technological regime is thus the technology-specific context of a technology which prestructures the kind of problem-solving activities that engineers are likely to do, a structure that both enables and constrains certain changes. Within this complex, the accommodation between its elements is never perfect; there are always tensions and a need for further improvement. The term regime is used rather than paradigm or system, because it refers to rules.[23] Not just rules in the form of a set of commands and requirements but also rules in the sense of roles and practices that are being established and that are not easily dissolved. Examples of such rules are the search heuristics of the engineers, the rules of the market in which firms operate, the user requirements to be accommodated at any give time, and the rules laid down by governments, investors and insurance companies. Like a political regime or a regulatory regime, a technological regime contains a set of rules. These rules guide (but do not fix) the kind of research activities that companies are likely to undertake, the solutions that will be chosen and the strategies of actors (suppliers, government and users).[24] The idea behind the technological regime is that the existing complex of technology extended in social life imposes a grammar or logic for socio-technical change, in the same way that the tax regime or the regulatory regime imposes a logic on economic activities and social behaviour. Our definition is thus more in line with the way in which the term regime is used in political science and policy studies.

Technological regimes, in the way we use the term, are a broader, socially embedded version of technological paradigms. A technological regime combines rules and beliefs embedded in engineering practices and search heuristics with the rules of the selection environment. In our view, the restricted (focused) nature of socio-technical change is accounted for in large part by the embedding of existing technologies in broader technical systems, in production practices and routines, consumption patterns, engineering and management belief systems, and cultural values—much more than it is by engineering imagination. This embedding creates economic, technological, cognitive and social barriers for new technologies.

The notion of technological regime defined above also helps to explain why most change is of the non-radical type, aimed at regime optimization rather than regime transformation. It helps to understand why so many new technologies remain on the shelf, especially systemic technologies with long development times that require changes in the selection environment (in regulation, consumer preferences, infrastructure, the price structure). Radically new technologies require changes in both the supply and demand sides, which usually take time and meet resistance, even inside the organization in which they are produced. Firms vested in the old technologies will be more inclined to reformulate their existing products than do something radically new that may involve a great risk to the firm. (For newcomers, the improvement of existing technologies creates an extra barrier for new technologies.) This is not to say that it is just a matter of calculated risk. As noted by Rosenberg and Fransman, firms have a restricted technological horizon and a bounded vision, which serve to focus their exploratory activities upon problems posed by the existing product.[25] As explained, there is a range of factors that work against the development and use of alternative technologies: cognitive (technological paradigms), technological, economic, and social and cultural barriers. This raises the question of how the above barriers may be overcome: how may the technology come into its own, develop from an idea or prototype into a successful product? The next section deals with this question.

The Management of Technological Regime Shifts

In this section, we want to examine how regime shifts occur. While there is no set of general rules, as each transition is unique, historical studies suggest that the following elements are common in technological regime shifts:[26]

- The deep interrelations between technological progress and the social and managerial environment in which they are put to use. Radically new technologies give rise to specific managerial problems and new user–supplier relationships; they require and lead to changes in the social fabric and often meet resistance from vested interests; moreover, they may give rise to public debates as to the efficacy and desirability of the new technology.
- The importance of specialized applications in the early phase of technology development. In the early phase of a radically new technology there is usually little or no economic advantage of the technology; moreover, the existing technologies tend to improve during the development phase (the 'sailing ship' effect).[27]
- These technologies tend to involve 'systems' of related techniques; the economics of the processes thus depend on the costs of particular inputs and availability of complementary technologies. Technical change in such related areas may be of central importance to the viability of the new regime.
- Social views on the new technology are of considerable importance. They include engineering ideas, management beliefs and expectations about the market potential, and, on the user side, perceptions of the technology. These beliefs and views on the new technology are highly subjective and will differ across communities. They also are in constant flux, and the progression of the ideas may be either a barrier or a catalyst to the development of a particular technology.

These elements show that in these technological transitions both the technology and the system in which it is produced and used change through a process of co-evolution and mutual adaptation. Although our understanding of how technological transitions come about is limited, historical evidence suggests that entrepreneurs/system builders and niches play an important role in the transition process.[28] The development of a new technological system is often associated with the names of entrepreneurs. For example, the names of Edison, Insull and Mitchell are associated with the development of the electric system. There was Edison, the inventor–entrepreneur, who built the first electric system, Insull, the manager-entrepreneur, who managed the expansion of the electric system, uniting local systems into larger ones, and Mitchell, the financier–entrepreneur, who introduced financial and organizational means (such as the holding company) by which the growth of the utility systems could continue on a regional level.[29]

A second important factor is the availability of niches or domains for application. Military demand often provided a niche for fledging technologies. Many of the radical technologies of this century (radio, aircraft and computers) depended for their development on money from the military. In other cases, early markets provided a niche. Plenty of examples of niches are available from the history of technology. The steam engine was developed by Newcomen to pump up water from mines; clocks were first used in monasteries where life was arranged according to strict timetables; the origin of the assembly line lies in the armoury of the American army in Springfield, Massachusetts, where the manufacture of muskets was standardized to the extent that all components were interchangeable; and the wheel was first used for ritual and ceremonial purposes.[30] These niches are important for the development of a new technology. Without the presence of a niche, system builders would get nowhere. The niches were instrumental in the take-off of a new regime and the further development of a new technology. Apart from demonstrating the viability of a new technology and providing financial means for further development, niches helped to build a constituency behind a new technology, and to set in motion interactive learning processes and institutional adaptations—in management, organization and the institutional context—that are all-important for the wider diffusion and development of the new technology.

The processes of niche formation occur against the backdrop of existing technological regimes. Often, some of the actors present in these regimes participate and attempts are made to solve problems identified but not solved within the regime. The success of niche formation is, therefore, linked to structural problems, shifts and changes within the existing regime(s). The ultimate fate of processes of niche formation depends as much on successful processes within the niche as on changes outside the niche: it is the coincidence of both developments that gives rise to niche development patterns.

The Problem of Technology Control and Orientation

It may be clear by now that the shift into a new, more sustainable technological regime presents a huge problem for public policy-makers (or anyone else, for that matter). The task is no longer to control or promote a single technology but to change an integrated system of technologies and social practices. The problem is to manage the change process to another regime without creating transition problems. This is the problem that public policy-makers face and must try to resolve. But how do they do this?

The first strategy is to change the structure of incentives in which market forces play. This is the kind of approach favoured by economists. Instead of engaging in the search for technologies to solve specific social problems, policy-makers should change the structure of economic incentives: tax negative externalities and reward positive externalities. The advantage of this strategy is that decisions are made at the decentralized level by individual actors. In this way, environmental benefits can be achieved at the lowest costs. The problem with this approach, favoured by economists, is that the policy measures have to be really drastic to have an impact, considering the dominance of existing technologies. Even the 10-fold increase in oil prices in the 1973–1983 period did not lead to anything more than the marginal use of alternative energy technology—coal and natural gas are still the primary sources for electricity generation and heating, and oil is still the principle transportation fuel. This is not to say that price incentives should not be used. In our view, a carbon tax and tradable permits will have a role to play in the array of necessary greenhouse gas policies, but it is not likely that such measures in themselves will be sufficient to bring about radical change in energy technology unless they significantly raise the costs of using fossil fuels. This is highly unlikely in today's political reality, in which governments are committed to reducing taxes. The recent failure in 1995 to introduce a carbon tax of US$3 per barrel of oil equivalent in the

European Union tells us something about the infeasibility of using taxes to induce technological regime shifts.

The second strategy is to plan for the creation and building of a new socio-technical regime, in the same fashion as decision-makers have planned for large infrastructural works like coastal defence systems or railway systems. The problem with this approach is that in most areas governments cannot really plan for a new technological regime in today's highly differentiated and organized society. The social context in which the new technologies will be used simply defies a planning exercise, even if it is based on a flexible learning by doing approach. Even for firms it is often difficult to plan for successful market introduction. User requirements develop over time in often unpredictable ways.

The third and last strategy is to build on the on-going dynamics of socio-technical change and to exert pressures so as to modulate the dynamics of socio-technical change into desirable directions. For this strategy, the task for policy-makers is to stimulate that the co-evolution of supply and demand produces desirable outcomes, in both the short run and longer term. Rather than laying down requirements, they need to engage in process management to keep the process of socio-technical change going in a desired direction.[31] Such a policy differs from the traditional policy approach, which starts from a stated goal, after which a set of instruments is selected to achieve this goal. Process management does not start from a quantified goal but from a stock of goals. It is aimed at changing the rules of the game, at creating room for experimentation and variation, at shaping the interactions, at making sure that the process is not dominated by certain actors, at learning about problems, needs and possibilities, and at keeping the process of change going in desirable directions. In our view, this is the only feasible way to proceed. Strategic niche management is thus more than a useful addition to a spectrum of policy instruments. It is a necessary and reflexive component of intentional transformation processes of regimes. However, the complexity of the processes involved means that we do not claim this approach to be a panacea. Its success is contingent on many developments outside the reach of policy-makers as well as other actors. We return to this issue later; we first discuss how process management could be done.

Our discussion of technological regime shifts as a process of niche proliferation suggests one possible strategy to manage the transition process: to create temporary protected spaces for more sustainable technologies. These spaces, in the form of technological niches, could function as local breeding spaces for new technologies, in which they get a chance to develop and grow. Once the technology is sufficiently developed in terms of user needs, and broader use is achieved through learning processes and adaptations in the selection environment, initial protection may be withdrawn in a controlled way. As suggested by Schot *et al.*,[32] such policies must be a mixture of three generic strategies: technology forcing, creating and using carrying networks for new technologies (such networks are called technological nexuses) and strategic niche management. The last is particularly interesting for the processes of niche formation. The first two also contribute, but are mainly instrumental in changing the existing regime by making them more favourable (less hostile) to the newly emerging niches. In this article, we focus on strategic niche management.

Strategic Niche Management as a Way to Manage the Transition

From our discussion of continuity and change in technological regimes, strategic niche management emerged as a possible (or even necessary) strategy for governments to manage the transition process to a different regime. The strategy of strategic niche management is, of course, valuable for an actor who wants to push new (sustainable) technologies on to the market. In this paper, we focus on options for government policies. But what exactly is meant by strategic niche management and what are the implications in terms of public policy? In this section, we try to explain what we mean by strategic niche management and how it may be used to induce or accelerate a change in technological regime. We propose the following definition: "strategic niche management is the creation, development and controlled phase-out of protected spaces for the development and use of promising technologies by means of experimentation, with the aim of (1) learning about the desirability of the new technology and (2) enhancing the further development and the rate of application of the new technology."[33]

Strategic niche management is thus a concentrated effort to develop protected spaces for certain applications of a new technology. It is an approach which differs from the old policies. The strategic niche management approach differs from the 'technology-push' approach that underlies most of today's technology promotion policies, by bringing knowledge and expertise of users and other actors into the technology development process and generating interactive learning processes and institutional adaptation. It differs from technology control policies by being aimed at the development of new technologies. The focus on learning is an important aspect of strategic niche management.[34]

The creation of a protected space for a promising technology gives it a chance to develop from an idea or showpiece in an exhibition into a technology that is actually used. The actual use of a new technology is important for articulation processes to take place, learn about the viability of the new technology and build a network around the product. Strategic niche management is more than just an experiment with a new technology, however. It is aimed at making institutional connections and adaptations, at stimulating learning processes necessary for further development and use of the new technology. More specifically, the aims of strategic niche management are:

- to articulate the changes in technology and in the institutional framework that are necessary for the economic success of the new technology;
- to learn more about the technical and economical feasibility and environmental gains of different technology options, i.e. to learn more about the social desirability of the options;
- to stimulate the further development of these technologies, to achieve cost efficiencies in mass production, to promote the development of complementary technologies and skills and to stimulate changes in social organization that are important to the wider diffusion of the new technology;
- to build a constituency behind a product—of firms, researchers, public authorities—whose semi-coordinated actions are necessary to bring about a substantial shift in interconnected technologies and practices.[35]

How does one create technological niches and manage them? First of all, it must be noted that niches are platforms for interaction; they emerge out of a process of interaction shaped by many actors. They cannot be controlled. Still, governments could try to contribute to these processes of niche formation by setting up a set of successive experiments with a number of new technologies; this is strategic niche management.[36] Such a policy consists of five steps (elements): the choice of technology, the selection of an experiment, the set-up of the experiment, scaling up the experiment and the breakdown of protection by means of policy. We now describe the elements, and the problems and dilemmas involved.

The Choice of Technology

There are usually different types of solutions for a problem, with different costs and benefits. A choice must be made as to which technology will be supported. Technologies appropriate for support through strategic niche management are technologies that are outside the existing regime or paradigm, but may greatly alleviate a social problem (like environmental degradation or road congestion) at a cost that is not prohibitively high. To be able to do so, the technology must meet four additional criteria, apart from the social precondition. The new technology must:

- have major technological opportunities embedded in it, have sufficient scope for branching and extension and for overcoming initial limitations—this is the technological-scientific precondition;
- exhibit temporal increasing returns or learning economies—the economic precondition;
- be consistent with actual or feasible forms of organization and control and be compatible with important user needs and values—the managerial and institutional precondition;
- be already attractive to use for certain applications in which the disadvantages of the new technology count less and the advantages are highly valued.

The first four preconditions—the social, technological-scientific, economic and managerial (or institution) preconditions—are preconditions for regime shifts, identified by Smith in the project 'Technological paradigms and transitions paths'. The fifth precondition is an additional precondition for the management of regime shifts through the creation and development of niches.

This step also shows a dilemma for strategic niche management. Strategic niche management is aimed at exploring options for co-evolution of technologies and its contexts. Creating path dependencies too early by focusing on a specific technology may lead to a mismatch between emerging application conditions and the chosen new technology. Strategic niche management as a transition tool rather than a market introduction strategy will have to allow for a variety of technological options and explorations of these options, while simultaneously working towards the embedding of these options.

The Selection of an Experiment

After choosing a technology eligible for support, we need to choose an appropriate setting in which the new technology is to be used. This should be a setting or space in which the advantages of the technology are valued highly (because of specific problems like local pollution) and the disadvantages (in terms of costs of discomfort) count less. The space may be a certain application (for example, the use of solar cells for pleasure boats), a geographical area (a region or a city) or a jurisdictional unit. The heterogeneity of the selection environment means that there are almost always areas and types of application for which the new technology is attractive, in which the disadvantages count less and the advantages are valued higher. Electric vehicles that do not emit pollutants at the point of use are attractive for use in cities with high levels of pollution. The disadvantages of electric vehicles, such as their low range and the need to recharge the batteries in charging stations, are less problematic for fleet owners (taxi companies, utilities, public transport companies) than for consumers. Consequently, the use of electric vehicles by fleet owners in cities qualifies as a societal experiment.

The Set-up of the Experiment

This is perhaps the most difficult step, because a balance must be struck between protection and selection pressure. Finding a balance between protection and selection pressure is a continuing task for niche managers. Protection should be not too generous: technology developers must be forced to take care of user requirements and impelled to eliminate negative side-effects connected with the wide-scale application of a new technology. On the other hand, the selection pressures should not be too strong, putting development work under time pressures and making companies opt for conventional solutions that offer short-term benefits at the expense of long-term benefits. Too much protection may in the end lead to expensive failures, and too little protection may forestall different paths of development.

The choice of niche policies needs to be based on the barriers to the use and diffusion of the new technology. These barriers may be economic, when the new technology is unable to compete with conventional technologies, given the prevailing cost structure. They may be technical, such as the lack of complementary technologies, needed new infrastructure or appropriate skills. And they may be social and institutional barriers, such as existing laws, practices, perceptions, norms or habits. An integrated and coordinated policy is required to deal successfully with these barriers. Possible elements of such a policy are the formulation of long-term goals, the creation of an actor network, coordination of actions and strategies and, where needed, the use of taxes, subsidies, public procurement and standards.

Scaling up the Experiment

The next step concerns scaling up the experiment by means of policy. Even a highly successful experiment may require some kind of support from public policy-makers in the form of preferential treatment *vis-à-vis* less environmentally benign technologies. Again, this raises the question of how far governments should go in support of a particular technology, such as whether they should bear the costs or let others carry part of the costs.

The Breakdown of Protection

The final step is the phased breakdown of protection. Support for the new technology may no longer be necessary or desirable when the results are disappointing and prospects are dim.

Who Should Do Strategic Niche Management?

Having described the steps of strategic niche management, we turn to the important issue of who should do strategic niche management: a government agency, private company or (policy) entrepreneur. In practice, different actors may be the niche manager: state policy-makers, a regulatory agency, local authorities (e.g. a development agency), non-governmental organizations (NGOs), a citizen group, a private company, an industry organization, a special interest group or an independent individual, depending on who is best qualified to take on this task, which will differ from case to case. It should be noted, however, that just like normal management, niche management is not the purview of a single actor but a collective endeavour. Niche management policies are the collective (negotiated) outcome of different interactions at different levels. Some actors, however, are likely to take on a more dominant role as niche managers than others, and may therefore be called 'niche managers'. The niche manager may be a person or an organization (for example, many projects have a so-called 'project bureau' that is formally in charge of the project management).

We wish to emphasize that strategic niche management is not just something for governments: industry and NGOs are well placed to initiate and run niche projects. As a rule, government should take on those roles that it can do better than others; it should not take on the responsibility for running the experiment, as this is probably best done by professionals with their own social networks. As noted, governments have a special role as a enabler or facilitator to make sure that something happens, and that the project yields satisfactory results (which requires monitoring, evaluation of outcomes and policies and, in the case of undesirable outcomes, the judicious exertion of pressure and the correction of adverse actions and policies). As to the role of different levels of government, local governments are best placed to engage in local affairs such as network management. Regional and state governments may act as co-sponsor for projects that may be used on a larger scale. They could also help in the upscaling of successful experiments, through sponsorship or macro-policies (like changes in the regulatory framework and the use of fiscal incentives). National and regional governments also have a special responsibility for making sure that there is a broad social learning process. This could be done by supporting a portfolio of niche projects, instituting technology appraisals and social discourses (in which the technologies are evaluated along a wide range of dimensions) and disseminating the knowledge that is gathered in the projects.

As a related point, the niche manager need not be the same person or organization during the niche management process; as the process moves along, there may be a need for a different niche manager.

With respect to the steps of strategic niche management, we wish to assert a warning: strategic niche management is more than the execution of the above five steps. If the execution of the steps was done too mechanically, the reflexive side of strategic niche management and its primary aims would be degraded. The primary aims of strategic niche management are stimulating learning about problems, needs and possibilities of a technology, building actor networks, alignment of different interest to a goal, altering the expectations of different actors and fostering institutional adaptation; the steps are just a way to achieve this. To elaborate on the primary aims of strategic niche management, we discuss three key processes in niche formation. Experiments set up as part of a strategic niche management policy must contribute to these processes in the various steps discussed.[37]

Processes Constituting Niche Formation

Coupling of Expectations

In the early years of development, the advantages of a new technology are often not evident. Their value still has to be proven, and there are many resisting forces. In order to map the new technology, the interested actors therefore make promises and raise expectations about new technologies. Promises of a new technology are an important element in niche development, and must, therefore, be taken up in strategic niche management procedures. Promises are especially powerful if they are shared, credible (supported by facts and tests), specific (with respect to technological, economic and social aspects) and coupled to certain societal problems which the existing technology is generally not expected to be able to solve. To couple expectations about technologies to societal problems, actors will translate their own expectations to other actors and engage in cooperation.[38] Furthermore, activities will be developed to substantiate the expectations; for example, by conducting research or by employing experts. When sufficient support has been gained and the niche has been formed, close attention has to be paid to the development of expectations. Niche formation and the development of a 'market of expectations' go together.

Articulation Processes[39]

We have pointed out that there are a number of barriers to the introduction and use of a new technology. It is important to learn more about these barriers and how they may be overcome. Many of the barriers involve uncertainty and perceptions. Learning—about needs, problems and possibilities—should thus be an important aim of niche management policies. Design specifications, user requirements and side-effects need to be articulated. The following articulation processes are particularly important:

(1) Articulation of technical aspects and design specifications. Which adjustments to the technology are required? What is the scope for learning, and for overcoming initial limitations?
(2) Articulation of government policy. What changes in the institutional structure and legislation are necessary to make an application of the technology possible or to stimulate its use? Should the government assume a different role?
(3) Articulation of cultural and psychological meaning. Which symbolic meaning can be given to the new technology? For example, can it be labelled and promoted as a safe and environmentally benign technology, as a 'feminine technology' and/or as a technology that fits a modern life-style?
(4) Articulation of the market: for whom (which users) is the new technology produced and what are the consumers' needs and requirements? How can the technology be marketed in an economically sound manner?
(5) Articulation of the production network: who should produce and market the new technology and fuel?
(6) Articulation of the infrastructure and the maintenance network: which complementary technologies, capabilities and infrastructure must be developed? Who looks after the maintenance of the new technology? Who is responsible for recycling or waste?
(7) Articulation of societal and environmental effects: what effects does the new technology have on society and the environment?

Experiments are a way to stimulate articulation processes that are necessary for the new technology to become socially embedded. An important aim of experiments should therefore be to stimulate the articulation of needs, problems and possibilities and to enact a broad learning process. For example, an experiment with electric vehicles in the Netherlands in the early 1990s resulted in a much clearer picture of the potential of electric vehicles. It featured a series of articulation processes: articulation of technical problems (malfunctioning of batteries in particular), articulation of user requirements and experiences (a clearer picture of for whom the technology would be attractive—fleet owners such as taxi companies, delivery firms), indications that technological limitations could be overcome (through changed driving behaviour and planning of trips, identification of regulatory constraints)[40] and, finally, suggestions as to how Dutch industry could benefit from the electric vehicle market.[41]

Network Formation

The development of a niche may also require the formation of a new actor network. Actors with vested interests in other technologies will generally not be interested in stimulating a new, competing technology. They may participate in the developments for defensive reasons but will show no real initiative. There are many examples of actors trying to slow down or even stop the niche from developing. In order to expand the niche, specific new actors must therefore often be involved in the affair, and the activities of the existing actors and their interactions ought to be changed. New network relations should be developed in which the new technology can function as desired. Public authorities could help to create such networks. They may also help to create and articulate a vision of where the sector or society should be heading. This would help to coordinate the strategies of technology developers, investors, regulators and users. In order to have a major impact, these visions must be accompanied by policy measures, such as the announcement of future regulations or taxes with respect to emissions and the setting of clear policy goals.

Care should be taken, however, that the development of the technology is not dominated by industry, but that the users and 'third parties' can also contribute their ideas. Among these third parties are the actors who are affected by the results of the technology, or organizations such as citizen groups and environmental groups.

Final Remarks

The niche policies should consist of a package of measures that deal with the different barriers in combination. The barriers should not be considered individually, lest we lose sight of the coherence and interaction between the different factors. Policies should also be aimed not just at changing the structure of incentives and constraints but far more at learning and coordination. Possible ways to do this are by bringing together different parties (firms, universities, research institutes) to work on a problem, providing financial assistance, and manipulating technological and economic expectations—for example, by securing a (future) market for a new product. In the case of technological controversies, they could arrange discussions between proponents and opponents to generate better understanding of the issues, and by doing so guide technology developers in their decisions. As noted, learning and institutional adaptation should be an important focus of policies. This will require a new role for public policy-makers, that of an enabling actor and catalyst rather than a regulator or technology sponsor. This new type of policy may be called a socio-technical alignment policy.[42] Within this perspective, the challenge of governments is not to maximize some imaginary welfare function but to ensure that the processes of co-evolution of technological supply and demand lead to desirable outcomes, in both the short term and the long run. This is also the approach of constructive technology assessment.[43]

In our view, strategic niche management is not just a useful addition to a spectrum of policy instruments: given the difficulties and disadvantages of other strategies, it may be the only feasible way to transform environmentally unsustainable regimes, even though strategic niche management in itself will not be likely to be sufficient to achieve a regime shift. To achieve a regime shift away from unsustainable practices, additional policies are needed, such as changes in the regulatory framework and state tax policies. Strategic niche management may help to pave the way for making such changes in state policies, by showing a possible solution to a problem. Thus, strategic niche management is more likely to act as a stepping stone, which facilitates—rather than forges—change in a new direction. But there are also problems with it, and these need to be pointed out. First, one must find a balance between protection and selection pressure. Too much protection may lead to expensive failures and too little protection may preclude or forestall different paths of development. This calls for on-going monitoring and evaluation of co-evolution processes and of the support policies themselves.

Second, there is no guarantee for success: changing circumstances may render the technology less attractive and technological promises may not materialize. Hence, it is important to promote technologies with ample opportunities for improvement, with a large cost-reduction potential that can be applied in a wide range of applications. Even if the technology does not yield short-term benefits, it may well be a useful technology in the longer term. This means that it is important to take a long-term perspective. For example, government support of electric vehicles has been criticized on the grounds that the environmental gains are limited and their performance is poor compared to internal combustion vehicles.[44] But this need not be true in a long-term vision, where electricity is generated by solar energy and advanced batteries become available. Improved batteries may also pave the way for hydrogen fuel-cell powered automobiles and wider use of solar energy.

Third, it may be difficult for governments to end the support for a technology because of the investments that have been made and resistance from those who have benefited from such programmes: the 'angry technological orphans' (as Paul David has called them) whose expectations have been falsely nourished.[45]

Fourth, it is important to create critical mass (sufficient momentum). To date, most experiments with alternative transport technologies have been rather small and have covered a short period of time. Experiments should be of sufficient size to allow for learning economies and to bring about institutional change. There is also a danger that the knowledge that is accumulated in the experiment is lost once the experiment is over.

Notes and References

1. For comments and suggestions, we would like to thank Boelie Elzen, Arie Rip, two reviewers and all project partners involved in the EU-SEER support project on strategic niche management.
2. Such systems consist of a fleet of vehicles that can be rented for short periods, and central management that controls their location and disposition. Examples are the Praxitèle and TULIP systems currently experimented with in France.
3. See, for example, A. Irwin & P. Hooper, 'Clean Technology, Successful Innovation and the Greening of Industry', *Business Strategy and the Environment, 1*, 1992, pp. 1–11; and K. Green & I. Miles, 'A Clean Break? From Corporate Research and Development to Sustainable Technological Regimes', in: R. Welford & R. Starkey (Eds), *Business and the Environment* (London, Earthscan Publications 1996), pp. 129–144.
4. A. H. van de Ven, 'Central Problems in the Management of Innovation', *Management Science, 32*, 1986, pp. 590–607.
5. See M. Hard & A. Knie, 'The Ruler of the Game: the Defining Power of the Standard Automobile', in: K. H. Sorensen (Eds), *The Past, Present and Future of the Motorcar in Europe* (Luxembourg, European Commission, 1994), pp. 137–158.
6. See W. J. Abernathy & J. M. Utterback, 'Patterns of Industrial Innovation', *Technology Review, 50*, 1978, pp. 41–47. See also J. M. Utterback, *Mastering the Dynamics of Innovation* (Boston, Harvard Business School Press, 1994).
7. See G. Dosi, 'Technological Paradigms and Technological Trajectories: A Suggested Interpretation of the Determinants and Directions of Technical Change', *Research Policy, 6*, 1982, pp. 147–162; G. Dosi, 'The Nature of the Innovation Process', in G. Dosi, C. Freeman, R. Nelson, G. Silverberg & L. Soete (Eds), *Technical Change and Economic Theory* (London, Pinter Publishers, 1988), pp. 221–238. R. R. Nelson & S. G. Winter, 'In Search of Useful Theory of Innovation', *Research Policy*,

6, 1977, pp. 36–76; R. R. Nelson & S. G. Winter, *An Evolutionary Theory of Economic Change* (Cambridge, MA, Bellknap Press, 1982).

8. Dosi, 1982, *op. cit.*, Ref. 7, p. 153.
9. Nelson and Winter, 1977, *op. cit.*, Ref. 7, p. 57.
10. G. Dosi, 'Sources, Procedures and Microeconomic Effects of Innovation', *Journal of Economic Literature, 26*, 1988, pp. 1120–1171.
11. For this reason, Rip and Schot have been advancing quasi-evolutionary theories based on a conceptualization of the interaction between selection environment and the variation process. In their conceptualization, variation and selection are neither independent nor coincidental processes. Selection may be anticipated, temporarily excluded or attenuated in the variation process (through processes of niche formation). In addition, institutional links exist between variation and selection, the so-called technological nexus. A. Rip, 'A Quasi-evolutionary Model of Technological Development and a Cognitive Approach to Technology Policy', *Rivista di Studi Epistemologici e Sociali Sulla Scienza e la Tecnologia, 2*, 1992, pp. 69–103; J. Schot, 'The Policy-relevance of the Quasi-evolutionary Model: The Case of Stimulating Clean Technologies', in: R. Coombs, P. Saviotti & V. Walsh (Eds), *Technological Change and Company Strategies* (London, Harcourt Brace Jovanovich, 1992), pp. 185–200; J. Schot, 'The Usefulness of Evolutionary Models for Explaining Innovation. The Case of The Netherlands in the Nineteenth Century', *History, and Technology*, forthcoming.
12. The discussion of these barriers and included empirical examples are taken from B. Elzen, R. Hoogma & J. Schot. *Mobiliteit met Toekomst. Naar een Vraaggericht Technologiebeleid*, Report for the Dutch Ministry of Traffic and Transport (The Hague, Ministerie van Verkeer en Waterstaat, 1996). The report will be available in English through a commercial publisher in 1998. For similar accounts of barriers, we refer to E. Tengström, *Why Have the Political Decision-makers Failed to Solve the Problem of Car Traffic?* (Gothenberg, University of Gothenberg, Reports in Human Technology no. 2, 1994), and Hard and Knie, *op. cit.*, Ref. 5.
13. Elzen *et al.*, *op. cit.*, Ref. 12.
14. The ZEV legislation may be changed to include hybrid-electric vehicles, to be defined as 'equivalent zero emissions vehicles'.
15. For this notion, see R. Kemp & L. Soete, 'The Greening of Technological Progress: An Evolutionary Perspective', *Futures, 24*, 1992, pp. 437–457.
16. Since an exhaust gas catalyst does not function well at low temperatures, pre-heating the catalyst markedly reduces the level of harmful emissions. The catalyst can be pre-heated with electricity from the grid or with a device that stores engine heat and releases it when the engine is started. Petrol cars can be equipped with a pre-heated catalyst without further changes to the vehicle. Alternative, cold-start emissions may be stored and treated when the catalyst is warmed up.
17. J. F. Porac, J. A. Rosa & M. S. Saxon, 'America's Family Vehicle: The Minivan Market as an Enacted Conceptual System', Paper for the Multidisciplinary International Workshop on Path Creation and Dependence, Copenhagen Business School, August 1997.
18. The typical range of a current generation electric vehicle is 100 km, the top speed 90 km/h, and charging takes some 6 hours. Refuelling a natural gas vehicle also takes longer than refuelling a conventional car. On the other hand, hybrid-electric cars have none of these disadvantages. Their market introduction could thus be as successful as that of the minivans. Even the cost aspect is comparable: minivans are substantially more expensive than conventional cars and so are hybrids expected to be.
19. Dosi, *op. cit.*, Ref. 7; Nelson & Winter *op. cit.*, Ref. 7.
20. Nelson & Winter, *ibid.*, p. 57.
21. The selection environment is also shaped by the experience of users and the adjustment of users (both companies and consumers) to particular technologies. For a discussion of co-evolution of technology and society, see A. Rip & R. Kemp, 'Technological Change', in: S. Rayner & E. L. Malone (Eds), *Human Choice and Climate Change, Volume II, Resources and Technology* (Washington DC, Batelle Press, 1998); and A. H. Molina, 'In Search of Insights into the Generation of Techno-economic Trends: Micro- and Macro-constituencies in the Microprocessor Industry', *Research Policy, 22*, 1993, pp. 479–506. Molina does not refer to the concept of co-evolution, but argues in similar way (pp. 483): "Sociotechnical constituencies may be defined as dynamic ensembles of technical

constituents (tools, machines, etc.) and social constituents (people and their values, interest groups, etc.), which interact and shape each other in the course the creation, production and diffusion of specific technologies. Thus the term 'sociotechnical consituencies' emphasises the idea of inter-relatedment. It makes it possible to think of technical constituents and social constituents stressing the point that in the technological process both kind of constituents merge into each other." Finally, we refer to R. Garud & M. A. Rappa, 'A Socio-cognitive Model of Technological Evolution: The Case of Cochlear Implants', *Organization Science*, *5*, 1994, pp. 344–362.

22. In Rip and Kemp, *op. cit.*, Ref. 21, the structured nature of a technological regime is accentuated by defining a technological regime as the coherent complex of scientific knowledges, engineering practices, production process technologies, product characteristics, skills and procedures, and institutions and infrastructures that are labelled in terms of a certain technology (for example, a computer), mode of work organization (for example, the Fordist system of mass production) or key input (like steel or hydrocarbons). Since the accommodation between the elements in the complex in never perfect, it is perhaps better to talk about a semi-coherent complex. For similar definitions see R. Kemp, 'Technology and the Transition to Environmental Sustainability. The Problem of Technological Regime Shifts', *Futures*, *26*, 1994, pp. 1023–1046; R. Kemp, *Environmental Policy and Technical Change. A Comparison of the Technological Impact of Policy Instruments* (Cheltenham, Edward Elgar, 1997).
23. Large technical systems as defined by Thomas Hughes can be seen as a special kind of regime, one in which material connections and the building up of an infrastructure are crucial to its diffusion. This creates special effects (the importance of load management), and leads to what Hughes has called momentum. T. P. Hughes, *Networks of Power. Electrification in Western Society 1880–1930* (Baltimore, Johns Hopkins University Press, 1983).
24. It is important to note that a technological regime does not fix technological choices, but is open to various kinds of change— at the level of regime components and even the overall architecture. Technological regimes change in conjunction with the evolution of social needs, technological possibilities and organizational change like new management systems.
25. See, Rosenberg 'The Direction of Technological Change: Inducement Mechanisms and Focussing Devices', in his book *Perspectives on Technology* (Cambridge, Cambridge University Press, 1976), pp. 108–125; and Fransman, *The Market and Beyond. Cooperation and Competition in Information Technology in the Japanese System* (Cambridge, Cambridge University Press, 1990).
26. R. Kemp, I. Miles, K. Smith *et al.*, Technology and the Transition to Environmental Stability. Continuity and Change in Complex Technology Systems, final report of the project 'Technological Paradigms and Transition Paths: The Case of Energy Technologies' for the SEER research programme of the Commission of the European Communities (DG-XII), 1994.
27. When steamships entered the market, sailing ship manufacturers stepped up their efforts to improve sailing ships in order to protect their business. This resulted in great improvements which helped sailing ships to survive the competition for a certain while.
28. See also A. Rip, 'Introduction of New Technology: Making Use of Recent Insights from Sociology and Economics of Technology', *Technology Analysis & Strategic Management*, *7*, 1995, pp. 417–431.
29. Hughes, *op. cit.*, Ref. 23.
30. For these and other examples see Schot, forthcoming, *op. cit.*, Ref. 11.
31. The use of process management as a means of social-political governance has been advocated by various policy scientists. See, for instance, J. Kooiman (Ed.), *Modern Governance. New Government–Society Interactions* (London, Sage, 1993); P. Glasbergen (Ed.), *Managing Environmental Disputes. Network Management as an Alternative* (Dordrecht, Kluwer, 1994).
32. J. W. Schot, B. Elzen & R. Hoogma, 'Strategies for Shifting Technological Systems. The Case of the Automobile System', *Futures*, *26*, 1994, pp. 1060–1076; and J. Schot & A. Rip, 'The Past and Future of Constructive Technology Assessment', *Technological Forecasting and Social Change*, 1997, pp. 251–268.
33. This definition is based on J. Schot, A. Slob & R. Hoogma, *Implementatie van Duurzame Technologie als een Strategisch Niche Management Probleem* (Den Haag, Programma Duurzame Technologische Ontwikkeling, 1994), Werkdocument CST3. The concept of strategic niche management is under development in the EU funded project 'Strategic Niche Management as a Tool for Transition to

a Sustainable Transport System'. For more information, contact the authors or visit the website: http://www.jrc.es/strategic niche management/.

34. We specifically include the adjective 'strategic' in the label of the approach, to stress the importance of anticipation. In running an experiment, the actors should adopt a forward-looking perspective, by anticipating emerging opportunities and possible threats that create, widen or close windows of opportunity.
35. See also K. Green, 'Creating Demand for Biotechnology: Shaping Technologies and Markets', in: Coombs *et al.*, *op. cit.*, Ref. 11, pp. 164–184.
36. See also M. Teubal, 'A Catalytic Evolutionary Approach to Horizontal Technology Policies', *Research Policy*, *25*, 1997, pp. 1161–1188. Teubal calls for technology policy as a succession of experiments (p. 1165).
37. Based on J. Schot *et al.*, *op. cit.*, Ref. 33.
38. For a discussion of technological expectations, see A. Rip, 'A Quasi-evolutionary Model of Technological Development and a Cognitive Approach to Technology Policy', *Rivista di Studi Epistemoligici e Sociali Sulla Scienza e la Technologia*, *2*, 1992, pp. 69–103; and H. van Lente, 'Promising Technology. The Dynamics of Expectations in Technological Developments', PhD thesis, Enschede, University of Twente, 1993.
39. For the notion of articulation process we refer to K. B. B. Clark, 'The Interaction of Design Hierarchies and Market Concepts in Technological Evolution', *Research Policy*, *14*, 1985, pp. 235–251.
40. Under the Dutch road tax system, electric vehicles fall in the heavily taxed 'rest' category; moreover, road vehicles are taxed according to their weight, which puts electric vehicles, with their heavy batteries, at a disadvantage. To take care of this problem, the Dutch government announced that it would give a tax break and investment subsidy to electric vehicles. A similar policy exists in the UK where electric vehicles are exempted from excise taxes.
41. See Schot *et al.*, 1994, *op. cit.*, Ref. 32.
42. See Rip & Kemp, *op. cit.*, Ref. 21; Molina, *op. cit.*, Ref. 21.
43. See A. Rip, Th. J. Misa & J. Schot, *Managing Technology in Society. The Approach of Constructive Technology Assessment* (London, Pinter Publishers, 1995).
44. See, for example, D. Wallace, *Environmental Policy and Industrial Innovation. Strategies in Europe, US and Japan* (London, Earthscan Publishers, 1995).
45. P. A. David, 'Path-dependence in Economic Processes: Implications for Policy Analysis in Dynamical System Contexts', CEPR discussion paper, Stanford, 1992.