Supplementary Material to

“A reduced-form approach for representing the impacts of wind and solar PV deployment on the structure and operation of the electricity system”

in Energy Economics

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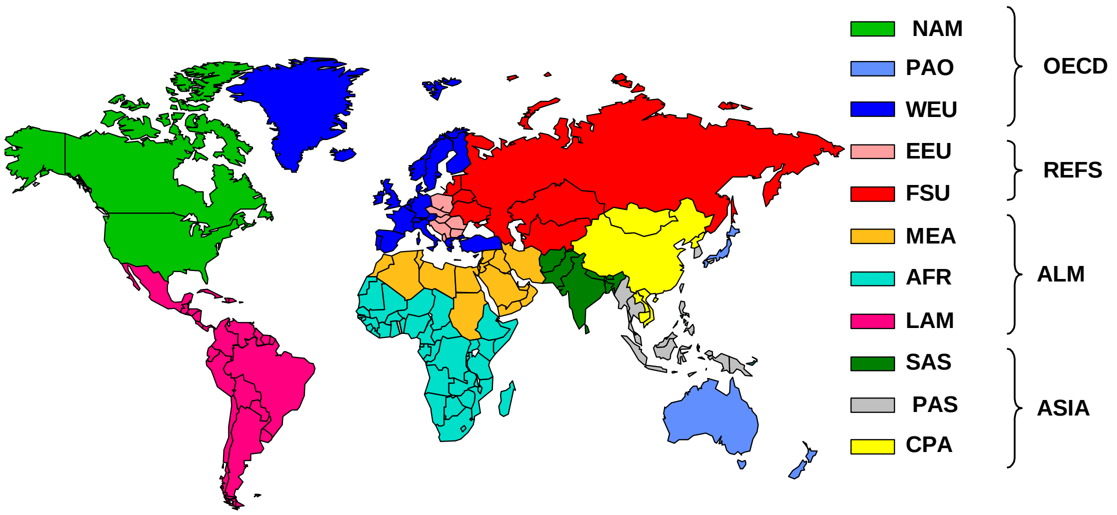
1. *Brief description of the MESSAGE integrated assessment modeling framework*

The MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) integrated assessment model (IAM) is a global systems engineering optimization model used for medium- to long-term energy system planning, energy policy analysis, and scenario development [1-3]. Developed at the International Institute for Applied Systems Analysis (IIASA) for more than two decades, MESSAGE is an evolving framework that, like other global IAMs in its class (e.g., MERGE, ReMIND, IMAGE, WITCH, GCAM, etc.), has gained wide recognition over time through its repeated utilization in developing global energy and emissions scenarios (e.g., Nakicenovic and Swart [4]).

The MESSAGE model divides the world into eleven (11) regions (Supplementary Figure 1, Table SM1) in an attempt to represent the global energy system in a simplified way, yet with many of its complex interdependencies, from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation. Trade flows (imports and exports) between regions are monitored, capital investments and retirements are made, fuels are consumed, and emissions are generated. In addition to the energy system, the model includes also the other main greenhouse-gas emitting sectors, agriculture and forestry. MESSAGE tracks a full basket of greenhouse gases and other radiatively active gases – CO_2 , CH_4 , N_2O , NO_x , volatile organic compounds (VOCs), CO, SO_2, PM, BC, OC, NH_3, CF_4, C_2F_6, HFC125, HFC134a, HFC143a, HFC227ea, HFC245ca, and SF_6 – from both the energy and non-energy sectors (e.g., deforestation, livestock, municipal solid waste, manure management, rice cultivation, wastewater, and crop residue burning). In other words, all Kyoto gases plus several others are included.



1 NAM North America
2 LAM Latin America & The Caribbean
3 WEU Western Europe
4 EEU Central & Eastern Europe
5 FSU Former Soviet Union
6 MEA Middle East & North Africa
7 AFR Sub-Saharan Africa
8 CPA Centrally Planned Asia & China
9 SAS South Asia
10 PAS Other Pacific Asia
11 PAO Pacific OECD

Supplementary Figure 1. Map of 11 regions in MESSAGE model

Table SM1. Listing of 11 MESSAGE regions by country

11 MESSAGE regions	Definition (list of countries)
NAM	**North America** (Canada, Guam, Puerto Rico, United States of America, Virgin Islands)
WEU	**Western Europe** (Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom)
PAO	**Pacific OECD** (Australia, Japan, New Zealand)
EEU	**Central and Eastern Europe** (Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Estonia, Latvia, Lithuania)
FSU	**Former Soviet Union** (Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan)
CPA	**Centrally Planned Asia and China** (Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Viet Nam)
SAS	**South Asia** (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka)
PAS	**Other Pacific Asia** (American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan (China), Thailand, Tonga, Vanuatu, Western Samoa)
MEA	**Middle East and North Africa** (Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen)
LAC	**Latin America and the Caribbean** (Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela)
AFR	**Sub-Saharan Africa** (Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Democratic Republic of Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia,

	Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe)

A typical model application is constructed by specifying performance characteristics of a set of technologies and defining a Reference Energy System (RES) that includes all the possible energy chains that MESSAGE can access. In the course of a model run, MESSAGE determines how much of the available technologies and resources are actually used to satisfy a particular end-use demand, subject to various constraints (both technological and policy), while minimizing total discounted energy system costs over the entire model time horizon (1990-2110). It does this based on a linear programming, optimization solution algorithm. The representation of the energy system includes vintaging of the long-lived energy infrastructure, which allows for consideration of the timing of technology diffusion and substitution, the inertia of the system for replacing existing facilities with new generation systems, clustering effects (technological interdependence) and – in certain versions of the model – the phenomena of increasing returns (i.e., the more a technology is applied the more it improves and widens its market potentials). Combined, these factors can lead to "lock-in" effects [5, 6] and path dependency (change occurs in a persistent direction based on an accumulation of past decisions). As a result, technological change can go in multiple directions, but once change is initiated in a particular direction, it becomes increasingly difficult to alter its course.

Important inputs for MESSAGE are technology costs and technology performance parameters (e.g., efficiencies and investment, variable, and O&M costs). For the scenarios included in this paper, technical, economic and environmental parameters for over 100 energy technologies are specified explicitly in the model. Costs of technologies are assumed to decrease over time as experience (measured as a function of cumulative output) is gained. For assumptions concerning the main energy conversion technologies see the following references: Riahi et al. [7], Nakicenovic and Swart [4], Riahi et al. [2], and van Vliet et al. [3]. For information on carbon capture and storage technologies specifically, see Riahi et al. [8].

MESSAGE is able to choose between both conventional and non-conventional technologies and fuels (e.g., advanced fossil, nuclear fission, biomass, and renewables), and in this respect the portfolio of technologies/fuels available to the model obviously has an important effect on the model result. In the version of the model used in this study, we consider a portfolio of technologies whose components are either in the early demonstration or commercialization phase (e.g., coal, natural gas, oil, nuclear, biomass, solar, wind, hydro, geothermal, carbon capture and storage, hydrogen, biofuels, and electrified transport, to name just a subset). Notably, this portfolio includes bio-CCS, a technology that can potentially lead to negative emissions (i.e., permanent underground storage of CO_2 which was originally pulled out of the atmosphere by photosynthesis). Exceedingly futuristic technological options, such as nuclear fusion and geo-engineering, are, however, not considered.

Other important input parameters for our modeling include fossil fuel resource estimates and biomass potentials. For fossil fuel availability, the model distinguishes between conventional and unconventional resources for eight different categories of (oil, gas, coal) occurrences [2, 9]. For biomass potentials we rely on spatially explicit analysis of biomass availability and adopt the assumptions discussed in Riahi et al. [2]. Updated wind and solar potentials are discussed in this paper.

Price-induced changes in energy demand (i.e., elastic demands) are also modeled in MESSAGE via an iterative link to MACRO, a top-down, macro-economic model of the global economy [10]. Through an iterative solution process, MESSAGE and MACRO exchange information on energy prices, energy demands, and energy system costs until the demand responses are such (for each of the six end-use demand categories in the model: electric and thermal heat demands in the industrial, residential, commercial, and transportation sectors) that the two models have reached equilibrium. This process is parameterized off of a baseline scenario (which assumes some autonomous rate of energy efficiency improvement, AEEI) and is conducted for all eleven MESSAGE regions simultaneously. Therefore, the demand responses motivated by MACRO are meant to represent the additional (compared to the baseline) energy efficiency improvements and conservation that would occur in each region as a result of higher prices for energy services. The macro-economic response captures both technological and behavioral measures (at a high level of aggregation), while considering the substitutability of capital, labor, and energy as inputs to the production function at the macro level.

Further and more detailed information on the MESSAGE modeling framework is available, including documentation of model set-up and mathematical formulation [1, 2] and the model's representation of technological change and learning [8, 11, 12]. The version of MESSAGE developed for this paper is labeled MESSAGE V.5b. This version builds upon MESSAGE V.3, which was used for the Global Energy Assessment (GEA) [13], and MESSAGE V.4, which includes soft constraints and the ability to conduct myopic scenarios [14]. MESSAGE V.5 has been developed within the context of the ADVANCE project and MESSAGE V.5b includes the updates to VRE integration as described in this paper.

2. *Seasonal and Short-term Curtailment Parameters*

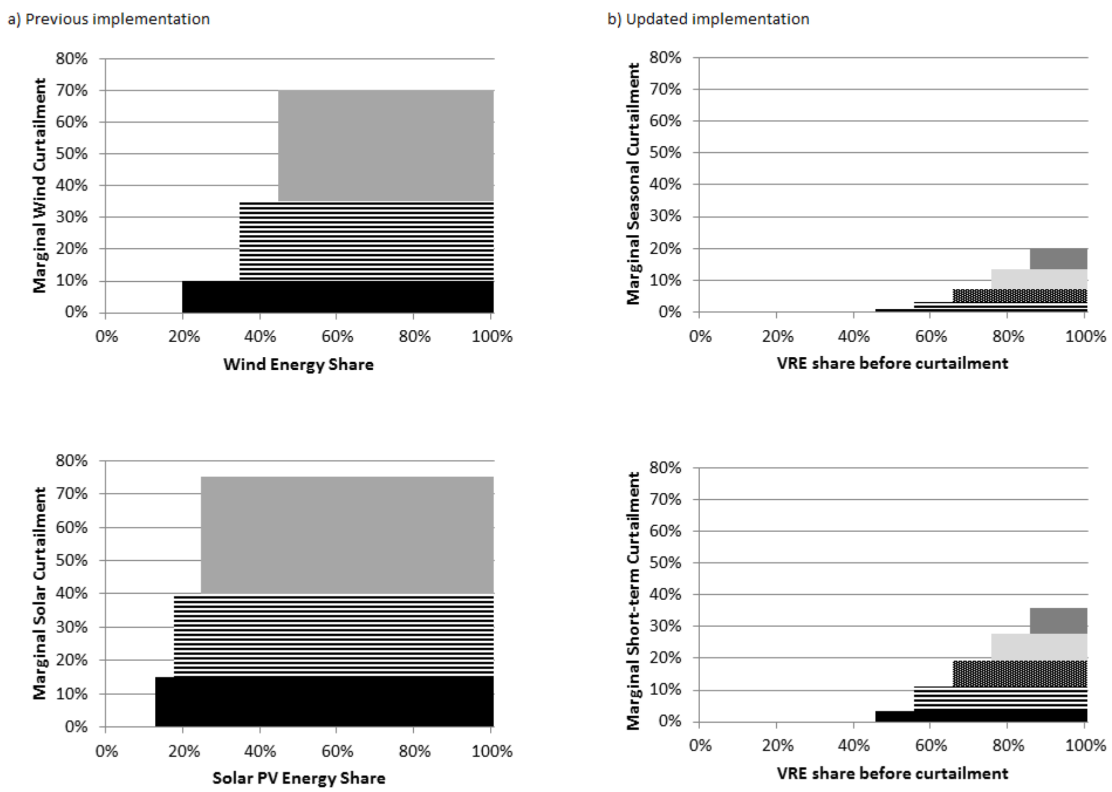
Table SM2: Seasonal and short-term curtailment parameters within each VRE market penetration step (defined by the share of VRE) for the updated MESSAGE implementation. The share of wind in VRE is the share of total VRE consisting of wind and represents the assumed range of wind/solar mixes for parameterizing curtailment in each region.

	Region										
	AFR	CPA	EEU	FSU	LAM	MEA	NAM	PAO	PAS	SAS	WEU
Share of Wind in VRE	83-94%	77-87%	90-100%	83-94%	75-90%	73-90%	72-92%	90-100%	62-69%	40-50%	80-93%
Short-term Curtailment (wcu)											
35-45%	0	0	0	0	0	0	0	0.060	0	0.030	0
45-55%	0	0.056	0.061	0.024	0.070	0	0.031	0.090	0.055	0.120	0.023
55-65%	0.023	0.058	0.065	0.063	0.071	0.020	0.080	0.093	0.056	0.121	0.067
65-75%	0.072	0.059	0.066	0.078	0.072	0.058	0.081	0.094	0.057	0.122	0.075
75-85%	0.085	0.060	0.067	0.079	0.073	0.083	0.082	0.095	0.058	0.123	0.076
>85%	0.086	0.061	0.068	0.080	0.074	0.085	0.083	0.096	0.059	0.124	0.077
Seasonal Curtailment (scu)											
35-45%	0	0	0	0	0	0	0	0	0	0.011	0
45-55%	0	0.011	0.011	0.004	0.019	0	0.006	0.052	0.010	0.027	0.004
55-65%	0.006	0.019	0.023	0.018	0.020	0.005	0.023	0.053	0.019	0.053	0.019
65-75%	0.025	0.039	0.043	0.041	0.050	0.021	0.043	0.054	0.038	0.085	0.039
75-85%	0.055	0.055	0.061	0.061	0.060	0.049	0.059	0.055	0.053	0.086	0.061
>85%	0.077	0.067	0.074	0.079	0.068	0.077	0.069	0.056	0.065	0.087	0.077

In contrast, the previous MESSAGE implementation considers only one type of curtailment, models curtailment independently for wind and solar PV, and assumes that CSP does not contribute to curtailment. The coefficients are indicated in Table SM3 and are identical for all regions. In the previous implementation, curtailment begins at a much smaller VRE share (13% vs. 35%) and ramps up much more quickly (Supplementary Figure 2). However, since curtailment is modeled independently for wind and solar, marginal curtailment will remain at 10-15% even when the wind share is 35% and the solar PV share is 18% for a total VRE share of up to 53%. Yet, the updated implementation would impose only 4% total curtailment at a similar VRE share, indicating that the previous implementation overestimates curtailment according to the RLDCs used in this study. Moreover, in the previous implementation, when the wind share exceeds 35% and/or the solar PV share exceeds 18%, the marginal curtailment quickly climbs to 35-40% of wind/solar PV generation, which discourages further investment in these technologies.

Table SM3: Wind and solar PV marginal curtailment parameters within each VRE market penetration step (defined by the share of VRE) for the previous MESSAGE implementation

	All regions
Wind Curtailment	
20-35%	0.1
35-45%	0.35
>45%	0.70
Solar Curtailment	
13-18%	0.15
18-25%	0.40
>25%	0.75



Supplementary Figure 2: Comparison of previous and updated representation of curtailment in MESSAGE. The updated implementation indicates the marginal curtailment for the NAM region, whereas the marginal curtailment parameters are identical in all regions in the old implementation. These figures indicate that curtailment penalties are much larger in the old implementation.

3. ***Firm Capacity Requirements***

Table SM4: Firm capacity requirements (including the reserve margin) in all regions and time periods as a multiplier of average annual load

	Time Period									
Region	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
AFR	1.58	1.64	1.65	1.65	1.66	1.62	1.62	1.62	1.61	1.60
CPA	1.46	1.50	1.54	1.58	1.61	1.62	1.62	1.63	1.63	1.64
EEU	1.90	1.81	1.77	1.75	1.76	1.74	1.73	1.72	1.70	1.70
FSU	1.74	1.68	1.69	1.70	1.72	1.70	1.68	1.67	1.66	1.64
LAM	1.61	1.67	1.69	1.71	1.73	1.71	1.70	1.69	1.69	1.68
MEA	1.86	1.83	1.79	1.77	1.75	1.73	1.72	1.72	1.72	1.73
NAM	1.87	1.81	1.80	1.79	1.78	1.77	1.77	1.76	1.76	1.75
PAO	1.94	1.85	1.78	1.73	1.70	1.68	1.67	1.66	1.66	1.66
PAS	1.62	1.71	1.69	1.68	1.68	1.67	1.66	1.65	1.65	1.64
SAS	1.59	1.63	1.63	1.65	1.68	1.68	1.68	1.68	1.69	1.69
WEU	1.79	1.75	1.74	1.72	1.71	1.69	1.68	1.67	1.66	1.65

4. *Wind and Solar Capacity Value Coefficients*

Table SM5: Marginal capacity value coefficients (fraction of capacity factor) for solar PV and wind in each region and deployment step (VRE share of total generation before curtailment) in the updated MESSAGE implmentation. Note that solar PV generally provides much less capacity value than wind, particularly at large shares.

	Region										
	AFR	CPA	EEU	FSU	LAM	MEA	NAM	PAO	PAS	SAS	WEU
Solar PV (scv)											
0-15%	0	0.209	0.101	0.101	0.486	0.006	1.501	0.433	0.209	0	0.101
15-50%	0	0	0.024	0.024	0	0.004	0.100	0.005	0	0	0.024
50-80%	0	0	0.002	0.002	0	0.003	0.006	0	0	0	0.002
>80%	0	0	0.002	0.002	0	0.002	0.005	0	0	0	0.002
Wind (wcv)											
0-15%	0.86	0.42	0.73	0.73	0.59	0.79	0.50	0.45	0.42	0.33	0.73
15-50%	0.58	0.37	0.51	0.51	0.35	0.62	0.43	0.22	0.37	0.23	0.51
50-80%	0.36	0.32	0.38	0.38	0.32	0.47	0.40	0.20	0.32	0.16	0.38
>80%	0.33	0.31	0.29	0.29	0.30	0.42	0.35	0.17	0.31	0.13	0.29

Wind capacity value supply curve:

(1) $WIND_1 \leq Elec_{TOT} * (0.15)$
(2) $WIND_1 + WIND_2 \leq Elec_{TOT} * (0.50)$
(3) $WIND_1 + WIND_2 + WIND_3 \leq Elec_{TOT} * (0.80)$
(4) $\sum WIND_x = \sum Elec_{WIND}$

Solar PV capacity value supply curve:

(1) $PV_1 \leq Elec_{TOT} * (0.15)$
(2) $PV_1 + PV_2 \leq Elec_{TOT} * (0.50)$
(3) $PV_1 + PV_2 + PV_3 \leq Elec_{TOT} * (0.80)$
(4) $\sum PV_x = \sum Elec_{PV}$

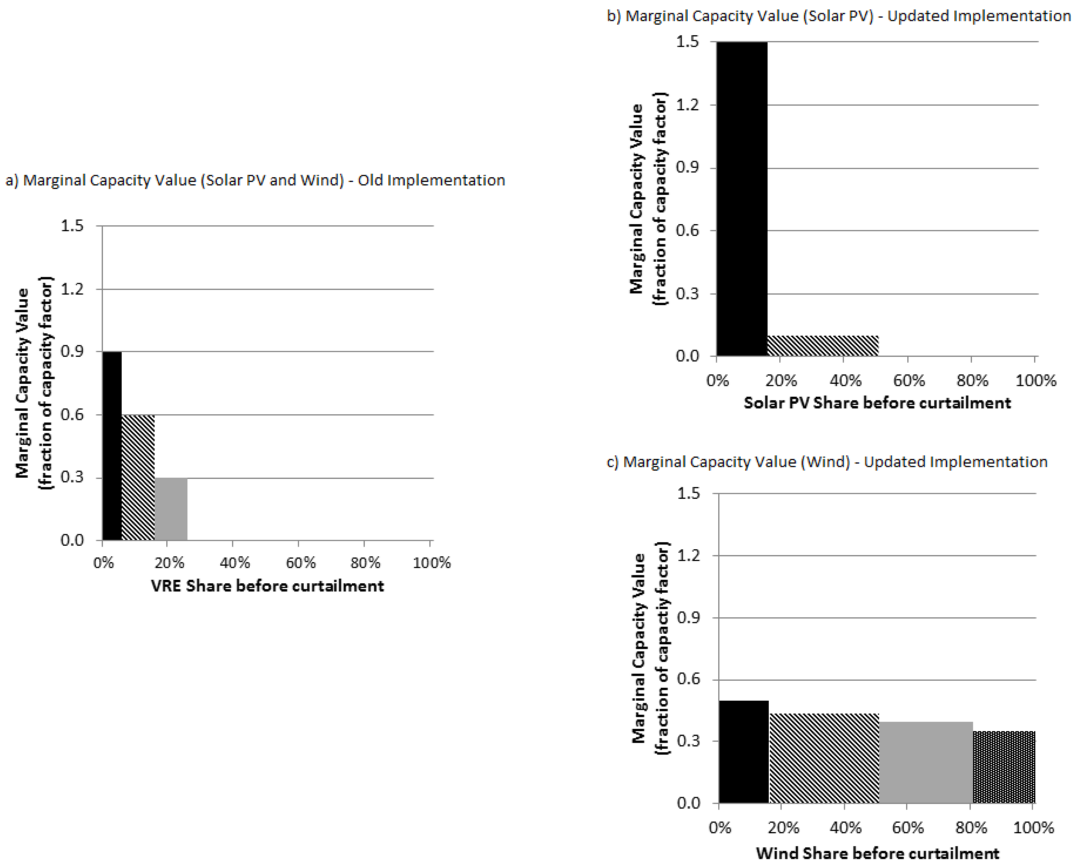
where:

$WIND_x$ = Electricity generated by wind in step x of wind capacity value supply curve
PV_x = Electricity generated by solar PV in step x of solar PV capacity value supply curve
$Elec_{TOT}$ = Total electricity entering the transmission grid
$Elec_{WIND}$ = Total electricity generated by all onshore and offshore wind resource classes
$Elec_{PV}$ = Total electricity generated by all solar PV resource classes

In contrast, the previous MESSAGE implementation uses the same marginal capacity value coefficients for both solar PV and wind and across all regions (Table SM6). Whereas the old implementation initially underestimates the capacity value of solar PV in North America, it greatly overestimates the capacity value in all other regions. Moreover, it overestimates the initial capacity value of wind in all regions, but greatly underestimates the marginal capacity value of wind at large shares. The old implementation indicates that the marginal capacity values of both wind and solar PV are zero above a 25% share and thus greatly underestimates the contribution of VRE to firm capacity at large shares, particularly for wind (Supplementary Figure 3). As a result, the old implementation discourages further investment in wind and solar PV beyond independent shares of 25% since each additional unit of VRE capacity would require one unit of backup firm capacity.

Table SM6: Marginal capacity value coefficients (fraction of capacity factor) for solar PV and wind in all regions and deployment steps (VRE share of total generation before curtailment) in the old MESSAGE implementation. Note that solar PV and wind have identical capacity values.

Wind/Solar PV Share	All regions
0-5%	0.9
5-15%	0.6
15-25%	0.3
>25%	0



Supplementary Figure 3: Comparison of old and updated MESSAGE implementations of wind and solar PV capacity values. The updated implementation indicates the marginal capacity values for the NAM region, whereas the parameters are identical in all regions in the old implementation.

5. *Operating Reserve Coefficients*

Table SM7: Operating reserve coefficients for VRE ($FLEX_{VRE}$) and load ($FLEX_{load}$) in each region for the updated MESSAGE implementation. Negative values indicate that more non-VRE flexibility is required with increasing VRE share while positive values indicate that less non-VRE flexibility is required. The bins (e.g., 0 - 15%) represent the VRE share of total annual generation before curtailment.

	Region										
	AFR	CPA	EEU	FSU	LAM	MEA	NAM	PAO	PAS	SAS	WEU
VRE (solar PV and wind)											
0 - 15%	0.05	-0.21	0.06	0.14	-0.24	0.07	-0.03	-0.35	-0.21	-0.65	0.16
15 - 50%	-0.29[1]	-0.53	-0.48	-0.35[1]	-0.48	-0.14[1]	-0.39	-0.67	-0.49	-0.86	-0.39[1]
> 50%	0.25[1]	0.31	0.33	0.28[1]	0.33	0.24[1]	0.29	0.36	0.30	0.22	0.29[1]
Load	0.12	0.13	0.20	0.20	0.18	0.18	0.19	0.17	0.13	0.05	0.20

[1] Second deployment bin is 15-60% and third bin is > 60%

The following equations describe the mixed integer formulation used to assign VRE flexibility requirements to each of the three deployment bins in each time period and region. The first set contains constraints that restrict the amount of electricity generation that can be assigned to each VRE deployment bin (equations 1 and 2) and ensure that VRE technologies are the suppliers of the electricity represented within these bins (equation 3) .

(1) $VRE_1 \leq Elec_{TOT} * Max_1$
(2) $VRE_1 + VRE_2 \leq Elec_{TOT} * Max_2$
(3) $\sum VRE_x = \sum Elec_{VRE}$

The second set of equations contains constraints to ensure that the VRE deployment bins must be exploited fully and in sequence. In these constraints, each deployment bin has a binary variable, which is 1 when the bin is fully utilized and 0 otherwise (equation 4). Equations 5 and 6 require that the binary variable associated with the previous bin must be set to 1 before the next bin can be accessed and equations 7 and 8 ensure that the deployment bins are filled in sequence. Finally, equations 9 and 10 restrict the binary variable associated with a particular bin from becoming 1 until the bin is fully utilized.

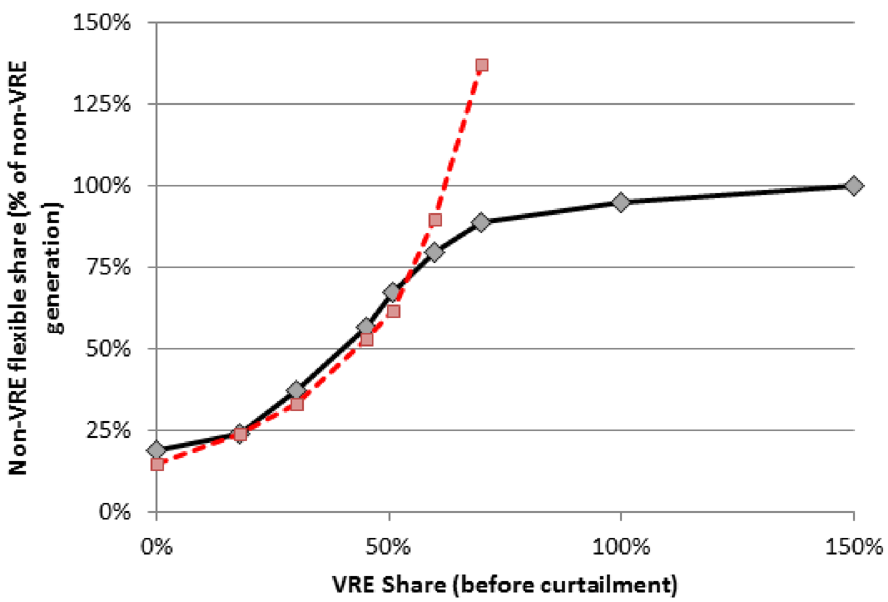
(4) $INT_x \in 0,1$
(5) $VRE_2 \leq INT_1(N)$
(6) $VRE_3 \leq INT_2(N)$
(7) $INT_2 \leq INT_1$
(8) $INT_3 \leq INT_2$
(9) $INT_1(N) - N + Elec_{TOT} * Max_1 \leq VRE_1$
(10) $INT_2(N) - N + Elec_{TOT} * Max_2 \leq VRE_1 + VRE_2$

where VRE_x is the electricity generated in bin x of the flexibility supply curve, $Elec_{TOT}$ is the total annual generation, Max_x is the maximum VRE share associated with bin x, $Elec_{VRE}$ is the total electricity generated by all solar PV and wind resource classes, INT_x is the binary variable representing bin x, and N is any large number greater than the maximum annual average load possible within all regions and time periods.

In contrast, the previous MESSAGE implementation provides independent operating reserve coefficients for solar PV and wind, yet uses the same coefficients for both technologies and across all regions (Table SM8). In addition, the old implementation does not use a mixed integer approach and thus the marginal non-VRE flexibility requirement increases with VRE share. As a result, the fraction of non-VRE generation that must be flexible exceeds 1 at 60-65% VRE share, meaning that excess electricity generation is required beyond this share (Supplementary Figure 4). This issue has been rectified in the updated implementation through the use of the mixed integer approach. The previous implementation yields similar non-VRE flexible shares up to a 50% VRE share. However, beyond this point, the two approaches diverge as the non-VRE flexible share begins to saturate in the updated implementation.

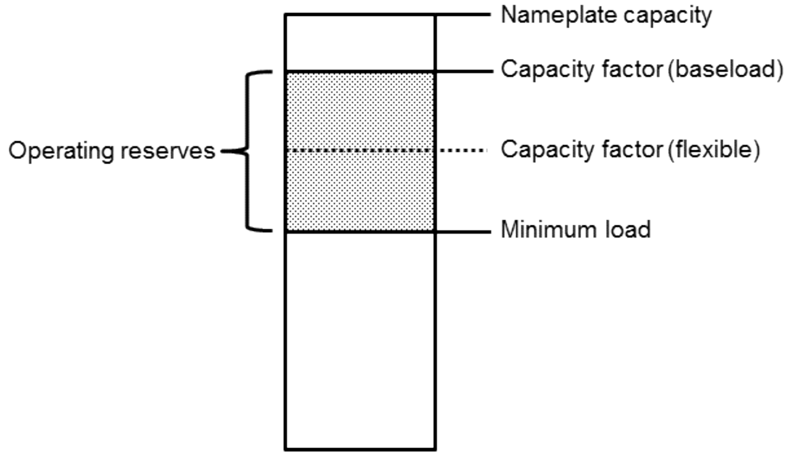
Table SM8: Operating reserve coefficients for VRE ($FLEX_{VRE}$) and load ($FLEX_{load}$) for all regions in the old MESSAGE implementation. Negative values indicate that more non-VRE flexibility is required with increasing VRE share. The bins (e.g., 5 - 15%) represent the wind or solar PV share of total annual generation before curtailment.

Wind/Solar PV Share	All regions
0-5%	-0.2
5-15%	-0.3
15-25%	-0.4
>25%	-0.5
Load	0.15



Supplementary Figure 4: Comparison of old (red dashed line) and updated (black solid line) MESSAGE implementations of non-VRE flexibility requirements, or operating reserves. The updated implementation indicates the non-VRE flexible share for the NAM region, whereas the trend is identical in all regions in the old implementation.

6. *Flexible Plant Operation*



Supplementary Figure 5: Schematic of assumptions regarding operating reserve and impact of flexible operation on the capacity factor

7. *Solar and Wind Resource Potentials*

Table SM9: Resource potential (EJ) by region and capacity factor for solar photovoltaic (PV) technology

	Capacity Factor (fraction of year)							
	0.28	0.21	0.20	0.19	0.18	0.17	0.15	0.14
AFR	0.0	1.1	46.5	176.6	233.4	218.2	169.9	61.9
CPA	0.0	0.0	0.0	10.3	194.3	315.5	159.4	41.9
EEU	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.0
FSU	0.0	0.0	0.0	0.2	2.8	23.6	94.9	116.6
LAM	0.1	4.9	49.4	165.6	157.5	167.4	81.4	48.5
MEA	0.2	3.1	100.8	533.6	621.8	310.1	75.3	14.5
NAM	0.0	0.3	24.3	140.4	131.0	116.3	155.7	106.4
PAO	0.0	0.0	0.1	2.2	53.1	226.4	311.2	158.9
PAS	0.0	0.0	0.0	0.2	0.8	17.0	31.2	12.8
SAS	0.0	0.0	6.1	42.7	67.2	82.3	23.7	4.1
WEU	0.0	0.1	0.2	3.0	12.8	39.4	58.3	33.3
Global	0.3	9.6	227.4	1074.7	1474.6	1516.3	1160.9	600.0

Table SM10: Resource potential (EJ) by region and capacity factor for concentrating solar power (CSP) technologies with solar multiples (SM) of 1 and 3

	Capacity Factor (fraction of year)							
SM1	0.27	0.25	0.23	0.22	0.20	0.18	0.17	0.15
SM3	0.75	0.68	0.64	0.59	0.55	0.50	0.46	0.41
AFR	0.0	3.6	19.0	81.6	106.7	62.8	59.6	37.8
CPA	0.0	0.0	0.0	0.0	0.0	0.3	11.5	53.0
EEU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FSU	0.0	0.0	0.0	0.0	0.0	0.1	0.4	6.1
LAM	0.0	2.0	7.0	11.8	29.3	57.1	56.8	53.5
MEA	0.1	3.7	24.8	122.4	155.3	144.5	68.4	34.0
NAM	0.0	0.0	0.0	6.3	19.7	20.2	29.6	43.2
PAO	0.0	3.0	75.1	326.9	158.3	140.4	40.2	10.2
PAS	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.6
SAS	0.0	0.0	0.0	0.1	3.9	8.7	16.1	9.8
WEU	0.0	0.0	0.0	0.0	0.2	0.7	2.4	3.0
Global	0.1	12.3	126.0	549.2	473.3	434.8	285.0	251.3

Table SM11: Resource potential (EJ) by region and wind class for onshore wind

	Wind Class					
	3	4	5	6	7	8+
AFR	38.2	21.3	13.4	6.8	2.6	2.1
CPA	24.7	11.4	5.4	2.6	0.3	0.0
EEU	6.1	5.7	0.3	0.0	0.0	0.0
FSU	52.3	83.8	5.8	0.8	0.0	0.0
LAM	33.5	15.9	9.6	5.7	3.9	3.7
MEA	56.1	22.2	6.0	2.1	0.9	0.3
NAM	28.6	66.4	23.7	1.5	0.4	0.0
PAO	18.9	18.8	3.6	1.4	1.8	0.5
PAS	5.2	2.9	0.8	0.2	0.0	0.0
SAS	12.3	7.9	2.4	1.6	0.9	0.3
WEU	16.1	10.5	6.6	8.2	3.7	0.6
World	292.1	266.8	77.5	30.9	14.3	7.5

Table SM12: Capacity factor by region and wind class for onshore wind

	Wind Class					
	3	4	5	6	7	8+
AFR	0.24	0.28	0.32	0.36	0.40	0.45
CPA	0.24	0.28	0.32	0.36	0.38	0.45
EEU	0.24	0.27	0.31	0.36	0.38	0.45
FSU	0.24	0.28	0.31	0.35	0.38	0.45
LAM	0.24	0.28	0.32	0.36	0.39	0.46
MEA	0.24	0.27	0.32	0.35	0.39	0.45
NAM	0.24	0.28	0.31	0.36	0.39	0.45
PAO	0.24	0.28	0.32	0.36	0.40	0.43
PAS	0.24	0.27	0.32	0.35	0.40	0.45
SAS	0.24	0.27	0.32	0.36	0.39	0.42
WEU	0.24	0.28	0.32	0.36	0.39	0.43

Table SM13: Resource potential (EJ) by region and wind class for offshore wind

	Wind Class					
	3	4	5	6	7	8+
AFR	3.1	2.4	2.0	2.0	1.1	1.7
CPA	3.5	4.3	2.6	0.9	1.3	0.1
EEU	0.7	0.6	1.0	0.0	0.0	0.0
FSU	1.8	4.6	14.2	13.3	4.3	0.7
LAM	7.1	7.3	5.3	2.7	2.6	5.9
MEA	3.2	0.9	0.8	0.9	0.6	0.9
NAM	4.5	18.2	24.0	16.0	7.3	2.1
PAO	5.8	11.2	15.3	9.8	2.6	2.5
PAS	5.3	6.6	4.7	1.5	0.1	0.0
SAS	1.9	0.9	0.6	0.5	0.0	0.0
WEU	3.5	4.7	8.8	12.9	10.3	0.9
World	40.4	61.5	79.4	60.5	30.3	14.8

Table SM14: Capacity factor by region and wind class for offshore wind

	Wind class					
	3	4	5	6	7	8+
AFR	0.24	0.28	0.32	0.36	0.41	0.47
CPA	0.24	0.28	0.32	0.36	0.40	0.42
EEU	0.24	0.29	0.32	0.34	0.40	0.42
FSU	0.25	0.28	0.32	0.35	0.39	0.43
LAM	0.24	0.28	0.32	0.36	0.40	0.49
MEA	0.24	0.28	0.32	0.36	0.40	0.45
NAM	0.25	0.28	0.32	0.36	0.40	0.43
PAO	0.24	0.28	0.32	0.36	0.40	0.47
PAS	0.24	0.28	0.32	0.35	0.39	0.42
SAS	0.24	0.27	0.32	0.36	0.40	0.42
WEU	0.24	0.28	0.32	0.36	0.40	0.42

8. Wind and Solar Overnight Capital Costs

Table SM15: Overnight capital costs ($/kW) for onshore wind

	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
AFR	1367	1129	987	903	856	830	808	794	786	781
CPA	1368	1154	1029	928	867	830	808	794	786	781
EEU	1465	1194	1029	928	867	830	808	794	786	781
FSU	1400	1167	1029	928	867	830	808	794	786	781
LAM	1379	1158	1029	928	867	830	808	794	786	781
MEA	1372	1143	1007	928	867	830	808	794	786	781
NAM	1465	1194	1029	928	867	830	808	794	786	781
PAO	1465	1194	1029	928	867	830	808	794	786	781
PAS	1384	1194	1029	928	867	830	808	794	786	781
SAS	1357	1127	990	911	867	830	808	794	786	781
WEU	1465	1194	1029	928	867	830	808	794	786	781

Table SM16: Overnight capital costs ($/kW) for offshore wind

	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
AFR	2050	1694	1481	1355	1283	1245	1212	1191	1179	1171
CPA	2052	1731	1543	1392	1301	1245	1212	1191	1179	1171
EEU	2198	1790	1543	1392	1301	1245	1212	1191	1179	1171
FSU	2100	1751	1543	1392	1301	1245	1212	1191	1179	1171
LAM	2068	1737	1543	1392	1301	1245	1212	1191	1179	1171
MEA	2059	1715	1510	1392	1301	1245	1212	1191	1179	1171
NAM	2198	1790	1543	1392	1301	1245	1212	1191	1179	1171
PAO	2198	1790	1543	1392	1301	1245	1212	1191	1179	1171
PAS	2076	1790	1543	1392	1301	1245	1212	1191	1179	1171
SAS	2035	1691	1486	1367	1301	1245	1212	1191	1179	1171
WEU	2198	1790	1543	1392	1301	1245	1212	1191	1179	1171

Table SM17: Overnight capital costs ($/kW) for solar PV

	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
AFR	2678	1965	1564	1342	1222	1161	1114	1088	1074	1065
CPA	2668	2016	1649	1389	1243	1161	1114	1088	1074	1065
EEU	2928	2109	1649	1389	1243	1161	1114	1088	1074	1065
FSU	2928	2109	1649	1389	1243	1161	1114	1088	1074	1065
LAM	2708	2030	1649	1389	1243	1161	1114	1088	1074	1065
MEA	2692	1996	1604	1389	1243	1161	1114	1088	1074	1065
NAM	2928	2109	1649	1389	1243	1161	1114	1088	1074	1065
PAO	2928	2109	1649	1389	1243	1161	1114	1088	1074	1065
PAS	2711	2109	1649	1389	1243	1161	1114	1088	1074	1065
SAS	2639	1953	1567	1355	1243	1161	1114	1088	1074	1065
WEU	2928	2109	1649	1389	1243	1161	1114	1088	1074	1065

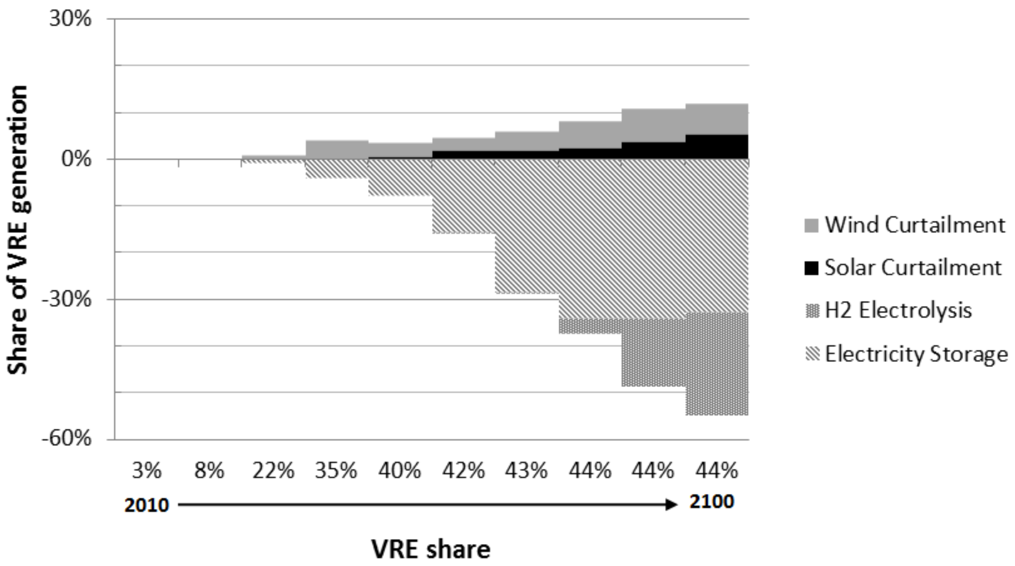
Table SM18: Overnight capital costs ($/kW) for solar CSP with a solar multiple of 1

	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
AFR	3972	3238	2735	2425	2269	2230	2269	2350	2433	2481
CPA	3983	3568	3248	3007	2834	2714	2634	2582	2542	2504
EEU	4747	4007	3466	3090	2846	2702	2623	2577	2530	2449
FSU	4459	3809	3334	3006	2795	2675	2617	2593	2574	2532
LAM	4609	3833	3285	2925	2714	2612	2582	2584	2579	2528
MEA	4069	3497	3088	2814	2650	2568	2543	2547	2555	2539
NAM	4660	3720	3157	2819	2617	2496	2423	2380	2354	2338
PAO	4660	3974	3461	3091	2837	2670	2562	2484	2407	2303
PAS	3905	3432	3091	2859	2714	2634	2598	2584	2569	2533
SAS	3905	3289	2862	2594	2450	2401	2413	2455	2495	2502
WEU	5665	4564	3766	3219	2871	2671	2566	2505	2437	2310

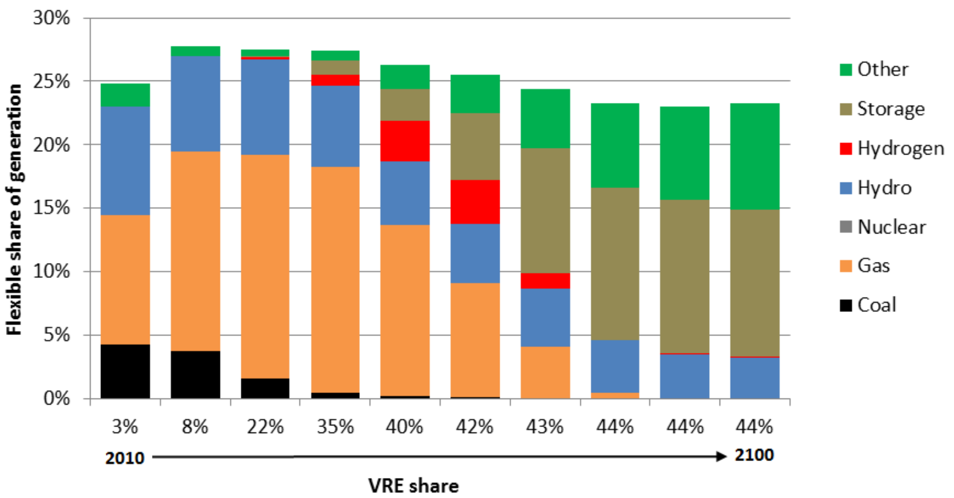
Table SM19: Overnight capital costs ($/kW) for solar CSP with a solar multiple of 3

	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
AFR	8465	6721	5516	4759	4361	4234	4291	4442	4599	4674
CPA	8583	7415	6531	5888	5444	5156	4982	4879	4806	4718
EEU	10229	8360	7002	6067	5471	5130	4958	4871	4785	4614
FSU	9610	7942	6730	5898	5373	5080	4948	4901	4867	4771
LAM	9932	8008	6645	5747	5216	4959	4881	4885	4877	4762
MEA	8768	7289	6229	5520	5092	4878	4809	4815	4830	4784
NAM	10042	7675	6295	5490	5021	4748	4589	4496	4442	4410
PAO	10042	8285	6985	6066	5453	5070	4843	4695	4552	4339
PAS	8414	7143	6225	5602	5215	5005	4914	4884	4856	4773
SAS	8414	6865	5785	5092	4709	4559	4562	4641	4718	4714
WEU	12207	9554	7640	6338	5522	5067	4848	4738	4614	4349

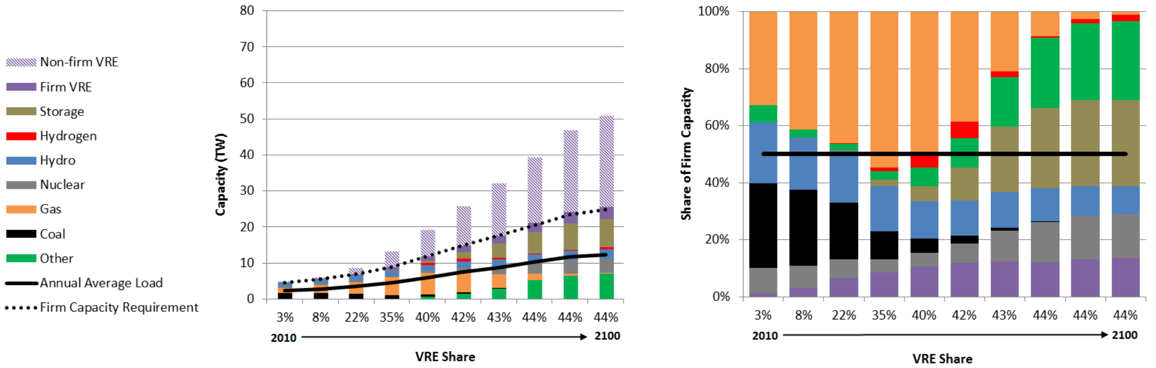
9. *Supplementary Figures for Old Integration Scenario*



Supplementary Figure 6: Theoretical wind and solar PV curtailment and electricity input to technologies that absorb curtailment (H_2 electrolysis and electricity storage) as a function of the VRE share of gross generation before curtailment for the Old Integration scenario. Theoretical curtailment is represented by positive values and the electricity input to technologies that absorb this curtailment is given as negative values. VRE shares are those associated with each decade between 2010 and 2100.



Supplementary Figure 7: Flexible share of gross generation as a function of VRE share of gross generation before curtailment for the Old Integration scenario. VRE shares are those associated with each decade between 2010 and 2100. Other includes geothermal, CSP, biomass, and oil. The flexibility constraint is not constrained and is met by gas power plants in early time periods. However, at 44% VRE share, the constraint is binding and is met primarily by electricity storage, hydropower, and flexible CSP with thermal storage.



Supplementary Figure 8: Capacity (TW) and share of firm capacity as a function of VRE share of gross generation before curtailment for the Old Integration scenario. VRE shares are those associated with each decade between 2010 and 2100. Other includes geothermal, CSP, biomass, and oil. The solid black line in all figures indicates the annual average load.

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