APPENDICES

THE ECONOMICS OF CLEAN ENERGY PORTFOLIOS

HOW RENEWABLE AND DISTRIBUTED ENERGY RESOURCES ARE OUTCOMPETING AND CAN STRAND INVESTMENT IN NATURAL GAS-FIRED GENERATION

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APPENDIX A - MARKET-SIZING METHODOLOGY

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Clean energy portfolio market-sizing methodology

To estimate the market size for clean energy portfolio technologies presented in Figure ES-3 and Figure 10, we used public data to parameterize a grid investment model that optimizes replacement of retiring assets with energy efficiency, demand flexibility, renewable energy, and energy storage. Distinct from the bottom-up case studies of four individual proposed power plants, the analysis presented here is top-down in that it assesses energy and capacity contributions on a fleetwide basis, and arrives at a conservative estimate for how many gas plants could be avoided by investment in DERs and renewable energy instead, at a national scale.

Retirement trajectory

- We used EIA Form 860 to estimate the average retirement age of fossil fuel-fired generators in the database that have been retired

- We then projected the year of retirement of each generator in service in 2016, based on its unit type average retirement date, from 2017 to 2030

Business-as-usual new build

- We assumed that, in the business-as-usual case, each retiring generator is replaced by either a new gas CCGT plant of equivalent megawatt capacity if the retiring resource has a high capacity factor, or a new gas CT plant if the retiring resource is a peaking plant. This assumption is conservative, based on recent EIA data: in the last 10 years, nearly twice the amount of new thermal power plant capacity has been added to the US fleet than has been retired

- We modeled the operation of the new fleet of gas power plants at the same capacity factor as the resources it is replacing, from 2017 to 2030

Clean energy portfolio market size

- To estimate the market size available to clean energy portfolios that mitigate gas investment, we made a number of resource-specific assumptions:

  - Energy efficiency is implemented nationwide at an incremental rate of 1% of sales per year, consistent with **leading utility performance**

  - We assumed ~60 GW of demand-flexibility capacity available to meet peak demand and reserve needs, approximately **equivalent to the existing market** and significantly lower than the **full potential** estimated by FERC

  - We assumed that new wind and solar projects make up 25% of total US electricity production by 2030, with 60% of that energy coming from wind, consistent with technically feasible scenarios from detailed NREL studies of the **eastern** and **western** interconnects

  - Using the resource-specific scenario assumptions, we modeled the annual investment in efficiency, demand flexibility, and renewables necessary to replace the energy production and capacity availability of the retiring thermal generators each year

Cost and performance estimates

- **New gas plants:** **Lazard's Levelized Cost of Energy, v10**, constant in real terms

- **Renewable energy:** **Lazard's Levelized Cost of Energy, v10**, with levelized costs assumed to fall in real terms by 28% (wind) and 47% (PV) by 2030, which are on the conservative end of analyst forecasts (e.g., Bloomberg New Energy Finance forecasts 60% and 33–37% reductions in LCOE, respectively, by 2030). We assume an average capacity factor of 42% (wind) and 28% (solar), consistent with recent projects

- **Demand flexibility:** We assume a constant, real $58/kW-y of levelized demand flexibility capacity costs, based on the Northwest Power and Conservation Council's **Seventh Power Plan** inputs

- **Energy efficiency:** We assume a constant, real $0.046/kWh total cost of saved energy, per **LBNL analysis** of utility programs across the US. We assume that energy efficiency portfolios save 1.23 kW on peak for each kW on average, per National Grid US estimates across a wide range of cost-effective measures (filed in **Docket 16-129, August 1, 2016**)

- **New transmission:** We assume an incremental, levelized transmission cost equivalent to $3.53 per MWh of new renewable energy, based on **NREL analysis** of national incremental transmission investment to accommodate ~30% of energy from renewables

- **Avoided transmission and distribution (T&D):** We assume that energy efficiency and demand response deployment offset $27/kW-y associated with behind-the-meter peak-load reduction, based on **RMI's previous meta-analysis** of average T&D benefits

Results

- We compare NPV costs through 2030 of the business-as-usual reinvestment pathway and the clean energy portfolio expansion scenario, and find ~$17 billion (~3%) in savings under the clean energy portfolio scenario using a 6% real discount rate

- We compare CO_2 emissions under the two scenarios, and find that clean energy portfolio expansion would eliminate 3.5 billion tons of CO_2 emissions through 2030, a reduction of 67% compared to business as usual

APPENDIX B - DATA INPUTS

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TABLE B-1
TYPES OF DATA INPUTS FOR THE ANALYSIS

DATA INPUT CATEGORY	DESCRIPTION	TYPES OF DATA SOURCES
Resource Potential	Inputs for estimating and bounding resource potential for EE, DR, and Renewables	End-use survey data; EE & DR measure impact data; Sector-level EE & DR potential; Renewable potential estimates
Resource Cost	Cost data for resources available in the portfolio and conventional resources, including CapEx, OpEx, and estimated cost declines where appropriate	Lazard LCOE and BNEF price forecasts; EIA AEO 2017 fuel prices; LBNL EE program cost survey data; FERC DR program cost survey data
Resource Parameters	Renewable production profiles, end-use load shapes, and DR operational assumptions	*Reinventing Fire*, originally sourced from NREL, proprietary load survey data, and RMI modeling of demand flexibility technologies
Case-Specific Parameters	*Reinventing Fire*, originally sourced from NREL, proprietary load survey data, and RMI modeling of demand flexibility technologies	Jurisdiction- and utility-specific planning documents and customer data; plant details

Resource potential: Sector-Level EE & DR, RE

TABLE B-2
EE SECTOR-LEVEL POTENTIAL, % OF SALES

SECTOR	YEAR	CASE 1	CASE 2	CASE 3	CASE 4
Industrial	2020	0.8%	0.6%	0.7%	1.1%
	2025	1.8%	1.4%	1.6%	2.3%
	2030	2.6%	2.0%	2.2%	3.4%
	2035	2.6%	2.0%	2.2%	3.5%
Residential	2020	2.3%	3.9%	2.8%	2.7%
	2025	2.3%	7.1%	4.9%	4.3%
	2030	3.7%	10.5%	7.8%	7.3%
	2035	4.2%	11.5%	8.8%	8.4%
Commercial	2020	4.9%	4.9%	4.4%	3.0%
	2025	7.3%	7.2%	6.5%	5.6%
	2030	7.5%	7.6%	6.9%	6.3%
	2035	7.6%	8.0%	7.3%	6.9%

Sources: EPRI State Level Electric Energy Efficiency Economic Potential Estimates

TABLE B-3
DR SECTOR-LEVEL POTENTIAL, % OF PEAK DEMAND

SECTOR	CASE 1	CASE 2	CASE 3	CASE 4
Industrial/Commercial	6.4%	4.5%	7.1%	6.3%
Residential	6.2%	13.1%	10.2%	8.6%

Sources: FERC National Assessment of Demand Response Potential

TABLE B-4
RENEWABLE ENERGY POTENTIAL

GW	CASE 1	CASE 2	CASE 3	CASE 4
Solar	2,800	2,488	4,435	20,409
Wind	31	0	1	1,166

Sources: NREL Estimating Renewable Energy Economic Potential in the US

Resource potential: EE & DR by end use

About this data: The model estimates EE and DR end-use potential with bottom-up estimates. This data is used to develop these potential values by end use.

TABLE B-5
END-USE UNITS/DEVICES PER CUSTOMER BY SECTOR

	END USE	CASE 1	CASE 2	CASE 3	CASE 4
Residential	Refrigerator	1.00	1.00	1.00	1.00
	Water Heat	0.31	0.73	0.73	0.54
	Lighting	5.42	12.21	12.21	12.77
	A/C (central)	0.49	0.82	0.82	0.82
	Space Heat	0.27	0.63	0.63	0.57
Commercial	Cooking	0.14	0.19	0.19	0.17
	Water Heat	0.47	0.61	0.61	0.43
	Refrigerator	0.69	0.72	0.72	0.67
	A/C	0.80	0.84	0.84	0.78
	Space Heat	0.39	0.51	0,51	0.42
	Lighting	18.64	26.39	26.39	19.87

Sources: Residential: EIA RECS; Commercial: EIA CBECS

About this data: Combined with the above data, this “impact per unit” data is used to develop MW of potential based on an estimated number of end-use units/devices. EE kW/unit values are the averages of the kW/unit peak-load reduction for EE measures in each end-use category. DR kW/unit are typical values for the peak operating load of efficient examples of equipment in each end-use category.

TABLE B-6

ENERGY SAVINGS AND PEAK REDUCTION PER END-USE UNITS/DEVICES

	END USE	EE kWh/UNIT	DR kW/UNIT
Residential	Refrigerator	480	
	Water Heat	594	3.0
	Lighting	52	
	A/C (central)	643	3.5
	Space Heat	1,805	3.0
Commercial	Cooking	3,978	
	Water Heat	3,936	6.0
	Refrigerator	1,078	
	A/C	2,932	4.0
	Space Heat	18,557	5.0
	Lighting	412	

Source: Expert judgment, survey data

Resource Cost: Generation

TABLE B-7

POWER PLANT COST INPUTS

BASIC INPUTS	
ASSUMPTION	**VALUE**
Inflation	2.00%
Discount Rate (Nominal)	8.15%
Current Year	2017

TYPE	ASSUMPTION	VALUE	UNIT	SOURCE	NOTES
PV Fixed	CapEx	1,040,000	$/MW	BNEF 1H 2017 LCOE Update - Solar	Low value
	CapEx Decline	4.6%	%/y		
	OpEx	9,000	$/MW-y	Lazard LCOE v11	Low value
	Life	30	years		
PV Tracking	CapEx	1,110,000	$/MW	BNEF 1H 2017 LCOE Update - Solar	Low Value
	CapEx Decline	4.6%	%/y		
	OpEx	12,000	$/MW-y	Lazard LCOE v11	Low Value
	Life	30	years		
Wind	CapEx	1,200,000	$/MW	Lazard LCOE v11	Low Value
	CapEx Decline	4.3%	%/y		Last Year
	OpEx	30,000	$/MW-y		Low Value
	Life	20	years		
Texas Wind Tx Adder	CapEx	1,445,000	$/MW	$20/MWh, 75% CapEx, 55% CF, 10.3% CRF	From Texas to Florida CCGT Case 2
	OpEx	24,000	$/MWh		
RE Tx Adder	CapEx	5	$/MWh	70% CapEx, 30% FOM	

TABLE B-7 (CONTINUED)

RESOURCE COST: GENERATION

BASIC INPUTS	
ASSUMPTION	**VALUE**
Inflation	2.00%
Discount Rate (Nominal)	8.15%
Current Year	2017

TYPE	ASSUMPTION	VALUE	UNIT	SOURCE	NOTES
NGCT	CapEx	875,000	$/MW	Lazard LCOE v11	Average
	FOM	5,000	$/MW-y		Low Value
	VOM	7.35	$/MWh		Average
	HR	8,902	Btu/kWh		
	Life	20	years		
NGCC	CapEx	1,000,000	$/MW	Lazard LCOE v11	Average
	FOM	5,850	$/MW-y		
	VOM	2.75	$/MWh		
	HR	6,517	Btu/kWh		
	Life	20	years		

Resource Cost: Energy storage

TABLE B-8

ES COST INPUTS (LI-ION)

BASIC INPUTS	
ASSUMPTION	**VALUE**
Inflation	2.00%
Discount Rate (Nominal)	8.15%
Current Year	2017

BNEF's ES CapEx Cost Decline is used exclusively because it is explicitly a long-term forecast. ES VOM includes what Lazard refers to as "augmentation costs," which are the equipment and/or operational costs required to maintain the system at the assumed performance level for 20 years.

		VALUE	UNIT	SOURCE	NOTES
Raw Data Inputs	CapEx Pack	307,000	$/MWh	Lazard LCOS v3	Low Value
	CapEx BoS	78,000	$/MW		Low Value
	FOM	2,750	$/MWh-y		Average
	Life	20	years		
	CapEx Pack	241,000	$/MWh	BNEF 2017 Global Energy Storage Forecast	
	CapEx BoS	305,600	$/MW		
	CapEx Decline	8.1%	%/y		
Data Inputs into the Model	2017 CapEx 4h	1,287,000	$/MW	Average (CapEx BoS from BNEF and Lazard) + Average (CapEx Pack from BNEF and Lazard) x 4 to quadruple energy capacity from 1 MWh to 4 MWh	
	2017 CapEx 6h	1,835,000	$/MW	Average (CapEx BoS from BNEF and Lazard) + Average (CapEx Pack from BNEF and Lazard) x 6 to increase energy capacity from 1 MWh to 6 MWh	
	2017 FOM 4h	11,000	$/MWh-y	4 x Average Lazard FOM	
	2017 FOM 6h	16,500	$/MWh-y	6 x Average Lazard FOM	
	2017 VOM	88	$/MWh	Augmentation cost, declines at same rate as CapEx	
	Life	20	years	Lazard LCOS v3	

Resource Cost: EE & DR

TABLE B-9
EE COST INPUTS

BASIC INPUTS	
ASSUMPTION	**VALUE**
Inflation	2.00%
Discount Rate (Nominal)	8.15%
Current Year	2017

In the case of Industrial EE and Residential Refrigerator EE, the average of the two provided values are used.

END-USE CATEGORY		LBNL CATEGORY	CSE $/MWh	LIFE
Industrial		IA: Prescriptive	30	10
Industrial		IA/Custom: Ind. &Ag. Process	30	14
Residential	Refrigerator	Res: Rebate/Appliances	30	11
Residential	Refrigerator	Res: Appliance Recycling	20	7
Residential	Water Heat	Res: Water Heater	70	12
Residential	Lighting	Res: Rebate/Lighting	10	7
Residential	A/C	Res: HVAC	20	15
Residential	Space Heat	Res: HVAC	20	15
Commercial	Cooking	Com/Prescriptive Other	20	12
Commercial	Water Heat	Com/Prescriptive Other	20	12
Commercial	Refrigerator	Com/Prescriptive Other	20	12
Commercial	A/C	Com/Pres: HVAC	30	13
Commercial	Space Heat	Com/Pres: HVAC	30	13
Commercial	Lighting	Com/Pres: Lighting	10	12

Source: LBNL, *The Program Administrator Cost of Saved Energy*
Note: Savings weighted average for each LBNL category, all values in 2012 $

Resource Cost: EE & DR

TABLE B-10
DR COST INPUTS

BASIC INPUTS	
ASSUMPTION	**VALUE**
Inflation	2.00%
Discount Rate (Nominal)	8.15%
Current Year	2017

END-USE CATEGORY		VALUE	UNIT	SOURCE	NOTES
Annualized Cost	Industrial	15,000	$/MW-y	EIA 861 (2016)	75th percentile for each sector
	Residential	12,146	$/MW-y		
	Commercial	9,875	$/MW-y		
Variable O&M		35	$/MWh	Expert Judgment	Conservative (high) estimate of wholesale cost of off-peak energy

Resource Cost: Fuel

TABLE B-11

FUEL PRICES, $/MMBtu

YEAR	COAL	GAS	OIL	URANIUM
2020	$2.56	$4.23	$4.74	$0.67
2021	$2.60	$4.34	$4.36	$0.71
2022	$2.66	$4.41	$3.67	$0.75
2023	$2.72	$4.54	$3.71	$0.80
2024	$2.77	$4.76	$3.99	$0.84
2025	$2.82	$4.96	$4.24	$0.90
2026	$2.89	$5.22	$4.58	$0.94
2027	$2.94	$5.52	$4.86	$0.99
2028	$3.00	$5.81	$5.16	$1.04
2029	$3.04	$6.10	$4.97	$1.07
2030	$3.10	$6.39	$5.34	$1.10
2031	$3.16	$6.76	$4.96	$1.15
2032	$3.21	$7.01	$5.21	$1.21
2033	$3.27	$7.17	$5.33	$1.27
2034	$3.34	$7.23	$5.85	$1.32
2035	$3.41	$7.40	$6.04	$1.39

Sources: EIA AEO 2017 Low Oil Price Scenario. Prices are nominal $/MMBtu

Resource Parameters

TABLE B-12
END-USE LOAD PROFILES

SECTOR	END USE
Industrial	All
Residential	Refrigerator
	Water Heating
	Lighting
	Space Cooling
	Space Heating
Commercial	Cooking
	Water Heating
	Refrigerator
	Space Cooling
	Space Heating
	Lighting

Note: Aggregation of all industrial end uses. *Reinventing Fire* load shapes originally developed using proprietary survey data on end-use patterns combined with regional EIA data.
Source: *Reinventing Fire*

TABLE B-13
RESOURCE PROFILES

SECTOR	DETAIL
Solar	PV Fixed
	PV Single Axis Tracking
Wind	Class 6 and 7 Wind Resources

Source: *Reinventing Fire*

PARAMETER	VALUE	UNIT	SIGNIFICANCE
DR Max	2	Hours	Maximum number of hours a DR resource can be used per day

Note: *Reinventing Fire* renewable profiles originally developed using hourly NREL model data from EWITS and WWSIS studies

Case 1 Parameters

TABLE B-14
CASE PARAMETERS

SYSTEM PARAMETER	VALUE
Region	West
Industrial Customers	9,000
Residential Customers	1,300,000
Commercial Customers	100,000
Sector EE/DR Allowable	80%
End-Use EE/DR Allowable	25%

TABLE B-15
BAU PLANT INPUTS

	VALUE
Type	CCGT
Built Year	2025
Capacity	600 MW

TABLE B-16
BAU CCGT CAPACITY FACTOR

MONTH	2025	2028	2031	2034	2037
January	66%	67%	69%	70%	70%
February	60%	59%	58%	57%	57%
March	57%	54%	52%	50%	50%
April	56%	54%	53%	52%	51%
May	55%	51%	48%	45%	44%
June	60%	56%	54%	52%	51%
July	67%	69%	69%	69%	68%
August	69%	72%	73%	75%	75%
September	65%	67%	67%	67%	67%
October	65%	65%	66%	65%	65%
November	67%	70%	73%	76%	78%
December	69%	72%	75%	78%	79%

TABLE B-17

ALLOWABLE EE & DR RESOURCE

END USE		EE MW	EE UNITS†	DR MW	DR UNITS†	TOTAL UNITS
INDUSTRIAL SECTOR*		**90**	**-**	**10**	**-**	**-**
RESIDENTIAL SECTOR*		**250**	**-**	**390**	**-**	**-**
	Refrigerator	20	370,000	-	-	1,300,000
	Water Heat	20	110,000	310	100,000	410,000
	Lighting	10	550,000	-	-	7,000,000
	A/C	60	170,000	550	160,000	630,000
	Space Heat	160	91,000	270	90,000	360,000
COMMERCIAL SECTOR*		**460**	**-**	**390**	**-**	**-**
	Cooking	-	-	-	-	14,000
	Water Heat	10	12,000	70	12,000	47,000
	Refrigerator	-	-	-	-	69,000
	A/C	40	21,000	80	20,000	80,000
	Space Heat	80	9,500	50	10,000	39,000
	Lighting	10	120,000	-	-	1,900,000

Note: * The allowable MW of sector-level EE/DR reflect 80% of the estimated resource potential while the end uses reflect 25% of resource potential.
† The number of units for each EE/DR end use are calculated by dividing the allowed EE/DR MW by the average per-unit impact of each EE/DR measure.

Case 2 Parameters

TABLE B-18
CASE PARAMETERS

SYSTEM PARAMETER	VALUE
Region	South
Industrial Customers	12,000
Residential Customers	4,300,000
Commercial Customers	550,000
Sector EE/DR Allowable	80%
End-Use EE/DR Allowable	25%

TABLE B-19
BAU PLANT INPUTS

	VALUE
Type	CCGT
Built Year	2022
Capacity	1,200 MW

TABLE B-20
BAU CCGT CAPACITY FACTOR

MONTH	2022	2024	2026	2028	2030
January	84%	85%	90%	91%	91%
February	84%	84%	90%	91%	91%
March	80%	79%	85%	86%	86%
April	84%	83%	87%	88%	88%
May	95%	94%	90%	90%	90%
June	99%	99%	93%	92%	92%
July	99%	99%	93%	92%	92%
August	99%	99%	93%	92%	92%
September	99%	99%	93%	92%	92%
October	96%	95%	92%	91%	91%
November	76%	75%	82%	84%	84%
December	89%	92%	93%	92%	92%

TABLE B-21

ALLOWABLE EE & DR RESOURCE

END USE		EE MW	EE UNITS[†]	DR MW	DR UNITS[†]	TOTAL UNITS
INDUSTRIAL SECTOR*		**310**	**-**	**20**	**-**	**-**
RESIDENTIAL SECTOR*		**2,700**	**-**	**2,900**	**-**	**-**
	Refrigerator	60	1,100,000	-	-	4,300,000
	Water Heat	150	760,000	2,350	780,000	3,100,000
	Lighting	80	3,800,000	-	-	53,000,000
	A/C	260	890,000	3,090	880,000	3,500,000
	Space Heat	1,870	670,000	2,020	670,000	2,700,000
COMMERCIAL SECTOR*		**2,100**	**-**	**980**	**-**	**-**
	Cooking	10	23,000	-	-	100,000
	Water Heat	70	81,000	500	83,000	340,000
	Refrigerator	20	81,000	-	-	400,000
	A/C	170	120,000	460	120,000	460,000
	Space Heat	1,240	70,000	350	70,000	280,000
	Lighting	100	1,100,000	-	-	15,000,000

Note: * The allowable MW of sector-level EE/DR reflect 80% of the estimated resource potential while the end uses reflect 25% of resource potential.
[†] The number of units for each EE/DR end use are calculated by dividing the allowed EE/DR MW by the average per-unit impact of each EE/DR measure.

Case 3 Parameters

TABLE B-22
CASE PARAMETERS

SYSTEM PARAMETER	VALUE
Region	South
Industrial Customers	6,000
Residential Customers	2,100,000
Commercial Customers	350,000
Sector EE/DR Allowable	80%
End-Use EE/DR Allowable	10%

TABLE B-23
BAU PLANT INPUTS

	VALUE
Type	CT
Built Year	2024
Capacity	475 MW

TABLE B-24
BAU CT CAPACITY FACTOR

MONTH	2024	2025	2030	2031	2032
January	0%	6%	7%	7%	7%
February	0%	5%	6%	7%	7%
March	0%	0%	0%	0%	0%
April	0%	0%	0%	0%	0%
May	0%	0%	0%	0%	0%
June	0%	1%	2%	5%	5%
July	0%	2%	3%	10%	10%
August	0%	1%	3%	9%	9%
September	0%	0%	1%	3%	3%
October	0%	0%	0%	0%	0%
November	0%	0%	0%	0%	0%
December	0%	2%	2%	2%	2%

TABLE B-25

ALLOWABLE EE & DR RESOURCE

END USE		EE MW	EE UNITS†	DR MW	DR UNITS†	TOTAL UNITS
INDUSTRIAL SECTOR*		**320**	-	**60**	-	-
RESIDENTIAL SECTOR*		**1,800**	-	**2,000**	-	-
	Refrigerator	10	180,000	-	-	2,100,000
	Water Heat	30	150,000	460	150,000	1,500,000
	Lighting	20	940,000	-	-	26,000,000
	A/C	50	170,000	600	170,000	1,700,000
	Space Heat	360	130,000	390	130,000	1,300,000
COMMERCIAL SECTOR*		**1,700**	-	**1,340**	-	-
	Cooking	10	12,000	-	-	66,000
	Water Heat	20	23,000	130	22,000	210,000
	Refrigerator	10	40,000	-	-	250,000
	A/C	40	28,000	120	30,000	290,000
	Space Heat	320	18,000	90	18,000	180,000
	Lighting	30	320,000	-	-	9,200,000

Note: * The allowable MW of sector-level EE/DR reflect 80% of the estimated resource potential while the end uses reflect 25% of resource potential.
† The number of units for each EE/DR end use are calculated by dividing the allowed EE/DR MW by the average per-unit impact of each EE/DR measure.

Case 4 Parameters

TABLE B-26
CASE PARAMETERS

SYSTEM PARAMETER	VALUE
Region	Texas
Industrial Customers	105,000
Residential Customers	9,700,000
Commercial Customers	1,350,000
Sector EE/DR Allowable	80%
End-Use EE/DR Allowable	2%

TABLE B-27
BAU PLANT INPUTS

	VALUE
Type	CT
Built Year	2020
Capacity	450 MW

TABLE B-28
BAU CT CAPACITY FACTOR

MONTH	2020	2022	2024	2026	2028
January	2%	2%	2%	2%	2%
February	3%	3%	3%	3%	3%
March	4%	4%	4%	4%	4%
April	12%	12%	12%	12%	12%
May	6%	6%	6%	6%	6%
June	7%	7%	7%	7%	7%
July	7%	7%	7%	7%	7%
August	10%	10%	10%	10%	10%
September	7%	7%	7%	7%	7%
October	3%	3%	3%	3%	3%
November	2%	2%	2%	2%	2%
December	1%	1%	1%	1%	1%

TABLE B-29

ALLOWABLE EE & DR RESOURCE

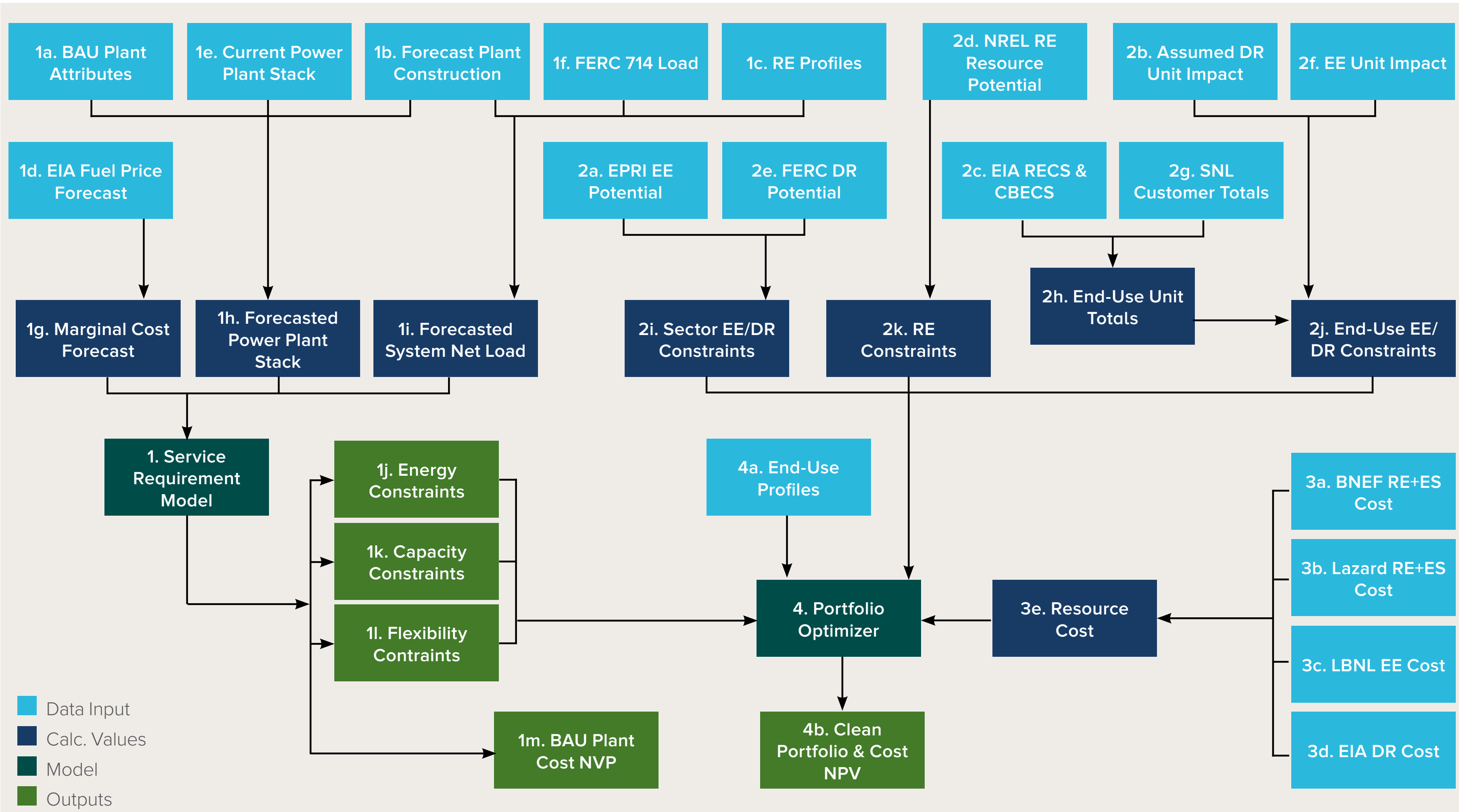
END USE		EE MW	EE UNITS†	DR MW	DR UNITS†	TOTAL UNITS
INDUSTRIAL SECTOR*		**1,100**	**-**	**50**	**-**	**-**
RESIDENTIAL SECTOR*		**3,400**	**-**	**5,500**	**-**	**-**
	Refrigerator	10	180,000	-	-	9,700,000
	Water Heat	20	89,000	320	110,000	5,300,000
	Lighting	10	510,000	-	-	120,000,000
	A/C	40	150,000	560	160,000	7,900,000
	Space Heat	370	110,000	330	110,000	5,500,000
COMMERCIAL SECTOR*		**5,000**	**-**	**3,950**	**-**	**-**
	Cooking	-	-	-	-	230,000
	Water Heat	10	11,000	70	12,000	580,000
	Refrigerator	10	36,000	-	-	910,000
	A/C	30	21,000	80	20,000	1,100,000
	Space Heat	260	11,000	60	12,000	570,000
	Lighting	20	210,000	-	-	27,000,000

Note: * The allowable MW of sector-level EE/DR reflect 80% of the estimated resource potential while the end uses reflect 25% of resource potential.
† The number of units for each EE/DR end use are calculated by dividing the allowed EE/DR MW by the average per-unit impact of each EE/DR measure.

APPENDIX C - CASE STUDY METHODOLOGY

APPENDIX C - CASE STUDY METHODOLOGY

FIGURE C-1
MODEL SCHEMATIC



Case Study Analysis Methodology Overview

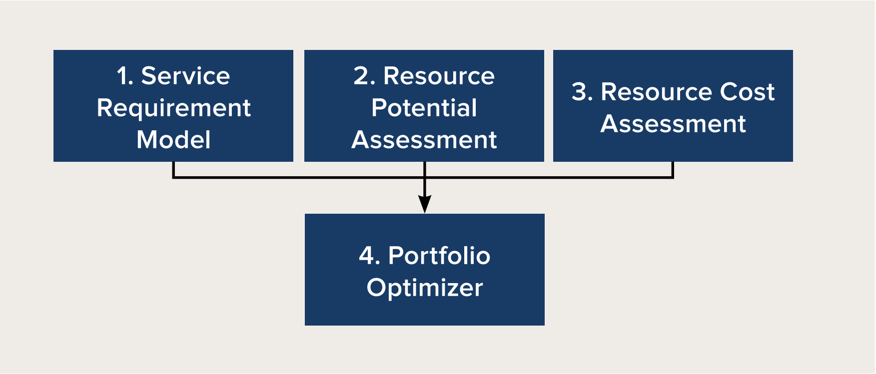
This analysis compares the NPV of cost for a proposed BAU power plant with a portfolio of DERs and utility-scale renewables ("clean portfolio"). The clean portfolio alternative is constructed to provide at least as much energy, capacity, and flexibility as the BAU plant.

Each case study analysis has four components: the service requirement model, resource potential assessment, resource cost assessment, and the portfolio optimizer. The analysis examines five model years to account for how system needs change over time and investigate the benefits of assembling resources incrementally to meet near-term needs.

1. The service requirement model estimates what energy, capacity, and flexibility services needed by the system will be provided by the BAU plant.
2. The resource potential assessment estimates the EE and DR resources available in the region for each sector and for each end use as well as the region's RE potential.
3. The resource cost assessment estimates the CapEx and OpEx of renewables, storage, EE, and DR resources available in the region and translates those costs for future years into present values.
4. The portfolio optimizer finds the lowest-cost portfolio of resources that can provide the energy, capacity, and flexibility services the BAU plant provided in the service requirement model using the available resources determined by the resource assessment.

FIGURE C-2

COMPONENTS OF CLEAN ENERGY PORTFOLIO OPTIMIZATION TOOL



Philosophy

Our goal in designing the model was to combine realism, conservatism, and tractability. One part of the model's conservativism lies in limiting the kinds of services the clean portfolio can provide to energy, capacity, and flexibility, ignoring many ancillary services as well as the potential benefits the clean portfolio might provide for the transmission and distribution system. By ignoring revenue and focusing exclusively on cost, we implicitly assume that the clean portfolio is only paid for the services that the BAU plant would have provided, and that any extra capacity, flexibility, and other services the clean portfolio could provide do not improve its economics in our comparison. This is likely a deeply conservative assumption, especially for storage, which can provide high-value ancillary services that we ignore. This reflects both conservatism in objective criteria but also in general approach, as we are careful not to build an operational model of a power system about which we have limited knowledge.

The cases are based on real proposed plants, at various stages of the planning process. We have rounded many actual parameters because the point of these studies is to demonstrate that a clean portfolio can obviate proposed plants in real-world systems, not to criticize specific jurisdictions or planning authorities.

Service Requirement Model

The service requirement model estimates the system net load, the power plant stack, and other factors that we use to determine the services the system needs the BAU plant to provide.

FIGURE C-3

SERVICE REQUIREMENT MODEL INPUTS AND OUTPUTS

INPUTS

- BAU plant attributes (1a)
- Thermal and RE capacity additions (1b)
- Regional hourly CF profiles for RE resources (1c)
- Forecasted fuel prices (1d)
- Current power plant stack (1e)
- 2016 system hourly load profile (1f)

OUTPUTS

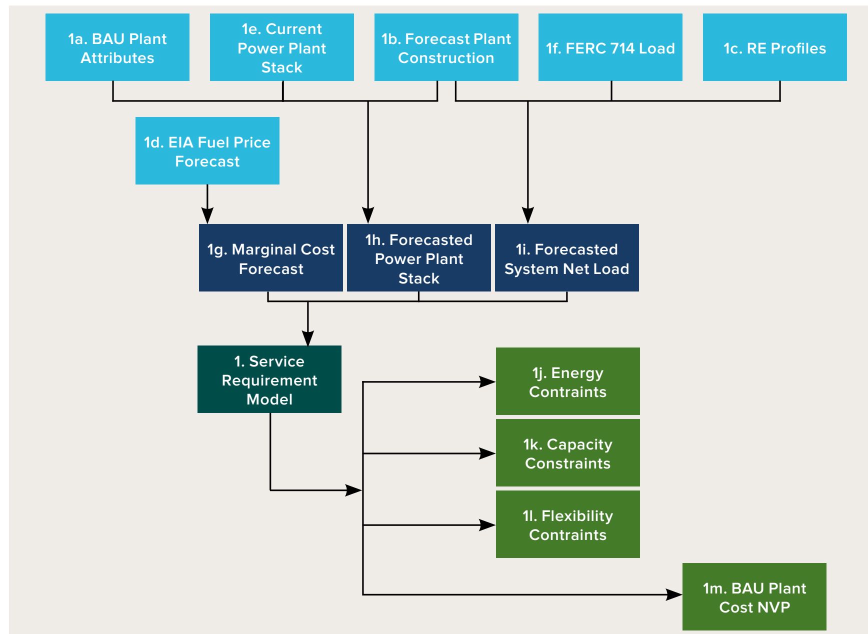
- Monthly energy requirements (1j)
- Hours for capacity constraints (1k)
- Hours for flexibility constraints (1l)
- BAU plant cost NPV (1m)

Description: The service requirement model begins by forecasting hourly system net load for each model year by applying load growth projections to the 2016 system load profile and subtracting projected renewable generation. We derive projected renewable generation from current RE capacity and planned capacity additions combined with hourly RE profiles. We use the top 50 hours of system net load for each model year in the capacity constraints, and the hour of highest system net load increase for each model year for the flexibility constraints.

For cases 1, 2, and 3, we base monthly energy requirements on the operating profile of the BAU plant as determined by the service requirement model and the planned capacity factor provided by the utility's IRP. For case 4, we base monthly energy requirements on average monthly capacity factors for similar CTs in the region.

FIGURE C-4

SERVICE REQUIREMENT MODEL SCHEMATIC



NOTE: The hourly profiles for 2016 remove 2/29. We estimate the operating profile of the BAU plant in each model year using the estimate of future net load together with marginal cost estimates for the fleet of resources that would serve this net load. Assuming strict economic dispatch on marginal cost, we determine which hours, and at what capacity the BAU plant would be dispatched given estimated net load.

Resource Potential Assessment

Determines the amount of EE and DR at the sector and end-use level appropriate to the specific case.

FIGURE C-5

RESOURCE POTENTIAL ASSESSMENT INPUTS AND OUTPUTS

INPUTS

- State/sector-level EE potential from EPRI (2a)
- State/sector-level DR potential from FERC (2e)
- Unit-level EE potential from DEP/TVA (2f)
- Assumed unit-level DR potential (2b)
- Customer totals from SNL (2g)
- RECS/CBECS end-use survey data (2c)

OUTPUTS

- Sector-level EE/DR constraints (2i)
- End-use-level EE/DR constraints (2j)

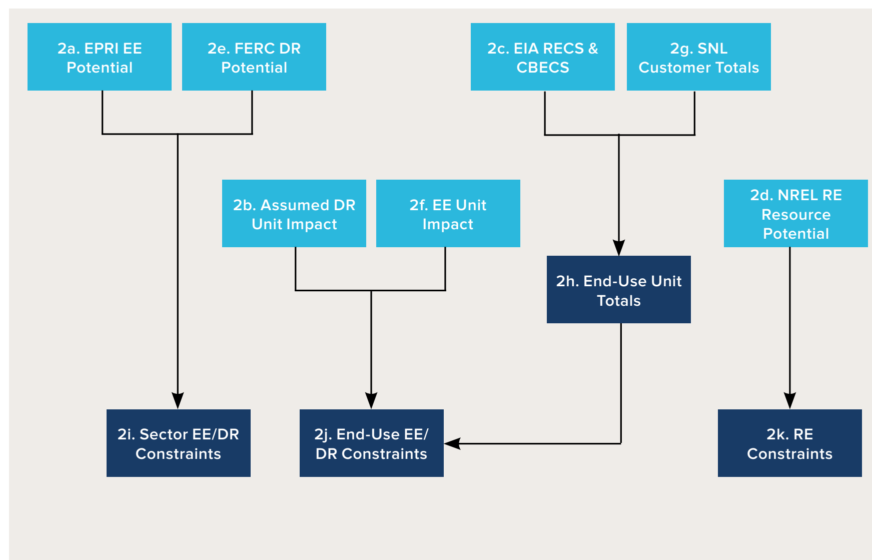
Description: The resource assessment performs bottom-up estimates of EE and DR potential by end use along with top-down potential estimates by customer sector. Top-down sector estimates for EE potential are calculated from EPRI state-level economic potential for EE savings by sector, which are percentages that we scale by the gross load from the service requirement model to determine sector-level potential.

Top-down estimates of achievable DR participation by sector are based on FERC-estimated shares of peak load that could be reduced by DR and our gross load from the service requirement model. Both DR and EE top-down potential estimates serve as sector-level limits on EE and DR resources available to the clean portfolio LP model. Bottom-up estimates for EE and DR are used to limit potential resources for a given end use.

For EE, these estimates are based on RECS 2015 and CBECS 2012 shares of households and businesses with a given electrical end use for the applicable region and SNL data on the number of customers for a given case study. Potential for these end uses is estimated by multiplying the number of devices by the assumed average peak reduction on a given end-use technology. DR end-use potential is estimated in the same fashion, with estimates of a number of devices from RECS and CBECS along with average peak reduction from enabling DR.

FIGURE C-6

RESOURCE POTENTIAL ASSESSMENT SCHEMATIC



Resource Cost Assessment

Converts and standardizes cost data into present values of CapEx and OpEx for each resource in each model year.

FIGURE C-7

RESOURCE COST ASSESSMENT INPUTS AND OUTPUTS

INPUTS

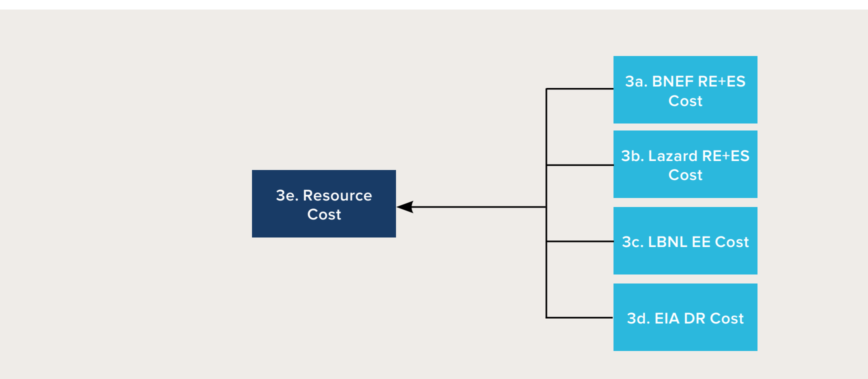
- Renewable and energy storage cost from BNEF (3a)
- Renewable and energy storage cost from Lazard (3b)
- Cost of saved energy from LBNL (3c)
- DR cost from EIA (3d)

OUTPUTS

- PV of CapEx and OpEx of each resource built in each model year (3e)

FIGURE C-8

RESOURCE COST ASSESSMENT SCHEMATIC



Description: Renewable and energy storage CapEx and OpEx costs and annual CapEx declines are taken from Lazard LCOE v11, Lazard LCOS v3, and Bloomberg New Energy Finance.

EE resource costs are based on estimated costs of running an effective EE program, and have a CapEx cost from incenting the deployment of EE measures but no OpEx costs. CapEx costs for particular EE end-use resources are based on the levelized-savings weighted-average costs from the LBNL PACSE study for the most similar measure category in the study. These levelized costs are converted to first-year costs with a capital recovery factor,[1] and scaled by annual energy saved by a single MW of that particular end use.

DR cost estimates are also program based, and calculated for each sector from 75th-percentile annual DR program costs in EIA's Form 861. We assume 10% of that cost is for fixed annual O&M, and the remainder is CapEx that can be de-annualized into a first-year cost with a capital recovery factor.[2] In addition to fixed O&M, DR OpEx includes variable O&M, which is based on an iterative estimate of how often DR would be dispatched.

CapEx for all resources are converted to present costs for each model year by inflating to the appropriate year, and decreasing capital costs where appropriate, and then discounting back to the current year. OpEx over the expected life of the resource is also inflated to the appropriate year, and discounted back to the current year.

See the following slide for a more detailed mathematical formulation, and Appendix B for the underlying data.

[1] Capital recovery factor based on LBNL's assumed discount rate (6%) and corresponding measure lifetimes.

[2] Capital recovery factor based on a 6% discount rate and a 10-year lifetime

Cost Assessment Mathematical Formulation

The costs of EE resources are assumed to be one-time costs, so the cost of saved energy for each end use found in the LBNL study must be converted from $/MWh into $/MW. Doing this requires that we take the cost of saved energy, multiply it by the amount of energy saved by one MW of EE for that end use, and then divide it by the capital recovery factor to get the CapEx value. For a particular end use u, the CapEx value k_{0,ee_u} is a function of its cost of saved energy κ_u, its annual energy savings eue_u, the upgrade's expected life n_u, and the discount rate r. The LBNL study provides all these values except for the annual energy savings. For these calculations, the 6% discount rate from the LBNL study is used. To calculate the energy saved by a MW of an EE end-use measure, we take a 8,760×12 matrix of capacity factors, normalized to their respective max values for the appropriate case. This matrix is defined as $\mathbf{EU}$, and is adapted from *Reinventing Fire*. Each column is an end use, and each row is an hour of the year. The column sums of $\mathbf{EU}$ represent the total energy saved by one MW of EE of each end use. We define a vector, $\mathbf{eue}$, as $\mathbf{EU}^{\mathrm{T}} \times \mathbf{1} = \mathbf{eue}$, which represents the amount of energy saved during a year by one MW of an EE measure for the corresponding 12 end uses.

$$k_{0,\mathrm{ee}_u} = \kappa_u \times eue_u \times \frac{(1+r)^{n_u} - 1}{r(1+r)^{n_u}} \tag{1.1}$$

The costs of DR resources are assumed to have CapEx components, as well as both fixed and variable operations and maintenance, FOM, and VOM respectively. The values from EIA give a single annual number that is assumed to include both CapEx and FOM, 90% being CapEx and 10% FOM. Unlike EE, the DR costs are only available at the sector level. For sector s, the CapEx value k_{0,dr_s} is a function of the annualized cost κ_s, the discount rate r and the program life, assumed to be 10 years. Again, a 6% discount rate is used.

$$k_{0,\mathrm{dr}_s} = 0.9\kappa_s \times \frac{(1+r)^{10} - 1}{r(1+r)^{10}} \tag{1.2}$$

DR OpEx is composed of both FOM and VOM. FOM is simple; it is just 10% of κ_s. But to define OpEx to include both FOM and VOM it is necessary to turn VOM into an annual cost. That means multiplying VOM by the number of hours per year it is used. It is assumed that DR can be used at most two hours per day. The only remaining value needed is the average number of cycles per day ν. The value of ν is determined for each case after running the LP with a value for ν of 0.25 and determining how often DR would actually need to be used during the year. ν is then updated and the process repeated until the LP results and the subsequent value of ν stop changing. That allows the definition of OpEx as o_{0,dr_s} with the following function:

$$o_{0,\mathrm{dr}_s} = 0.1\kappa_s + vom_{\mathrm{dr}} \times 2 \times 365 \times \nu \tag{1.3}$$

With the cost of each resource calculated for the current year, it is necessary to inflate these costs to what their values would be in each model year, and then discount those values back to the present in order to get comparable present values. The CapEx value in year y for resource j is found via the following equation:

$$k_{y,j} = k_{0,j} \left[(1-\rho_j) \left(\frac{1+\mu}{1+r} \right) \right]^{m_y - m_0} \tag{1.4}$$

Where r is the model discount rate, μ is the inflation rate, m_0 is the current calendar year, m_y is the calendar year of model year y, and ρ_j is the predicted compound annual decline in CapEx for resource j. The OpEx for units of resource j with an expected life of n_j put into service in year y can be defined as follows:

$$o_{y,j} = o_{0,j} \sum_{l=1}^{n_j} \left(\frac{1+\mu}{1+r} \right)^{l+m_y-m_0} \tag{1.5}$$

The OpEx for energy storage is different because it includes both a constant FOM and a declining VOM. We define o_{y,es_ω} which is the OpEx for 1 MW of energy storage with ω hours of capacity in year y as follows:

$$o_{y,\mathrm{es}_\omega} = \omega \times fom_{\mathrm{es}} \sum_{l=1}^{n_{\mathrm{es}}} \left[\frac{(1+\mu)^l}{(1+r)^{l+m_y-m_0}} \right] + \nu_{\mathrm{es}} \times \omega \times vom_{\mathrm{es}} \sum_{l=1}^{n_{\mathrm{es}}} \left[\frac{(1+\mu)^l (1-\rho_{\mathrm{es}})^{l+m_y-m_0}}{(1+r)^{l+m_y-m_0}} \right] \quad (1.6)$$

Where ν_{es} is the number of full charge/discharge cycles the battery completes in one year, this value is 350 when the BAU plant is a combined-cycle gas turbine and 90 when the BAU plant is a combustion turbine. For wind and solar, we assume that both incur transmission charges of \$3.50/MWh in CapEx and \$1.50/MWh in FOM. For RE resource j, the CapEx for year y is calculated as follows:

$$k_{y,\mathrm{re}_j} = \left(\frac{1+\mu}{1+r} \right)^{m_y-m_0} \left[k_{0,\mathrm{re}_j} (1-\rho_{\mathrm{re}_j})^{m_y-m_0} + 3.5 \times 8766 \times cf_{\mathrm{re}_j} \frac{(1+r)^{n_{\mathrm{re}_j}}-1}{r(1+r)^{n_{\mathrm{re}_j}}} \right] \quad (1.7)$$

Where cf_{re_j} is the capacity factor of RE resource j. The OpEx for units of RE resource j put into service in year y is calculated as follows:

$$o_{y,\mathrm{re}_j} = \left(fom_{\mathrm{re}_j} + 1.5 \times 8766 \times cf_{\mathrm{re}_j} \right) \sum_{l=1}^{n_{\mathrm{re}_j}} \left(\frac{1+\mu}{1+r} \right)^{l+m_y-m_0} \quad (1.8)$$

Portfolio Optimizer

Determines the lowest-cost clean portfolio that meets the needs determined by the service requirement model with the available resources determined by the resource potential assessment. Includes postprocessing to calculate metrics on the portfolio and assessing the amount of additional energy.

As a postoptimization step, the model assesses how much energy the portfolio produces beyond the service requirement. We determine whether there is sufficient additional energy to enable the demand flexibility and energy storage dispatch profiles assumed by the model. Any remaining additional energy has its value estimated based on the methodology on the following page.

FIGURE C-9

PORTFOLIO OPTIMIZER INPUTS AND OUTPUTS

INPUTS

- Resource costs (3e)
- RE resource potentials (2k)
- End-use EE/DR resource potentials (2j)
- Sector EE/DR resource potentials (2i)
- Energy constraints (1j)
- Hours for capacity constraints (1k)
- Hours for flexibility constraints (1l)

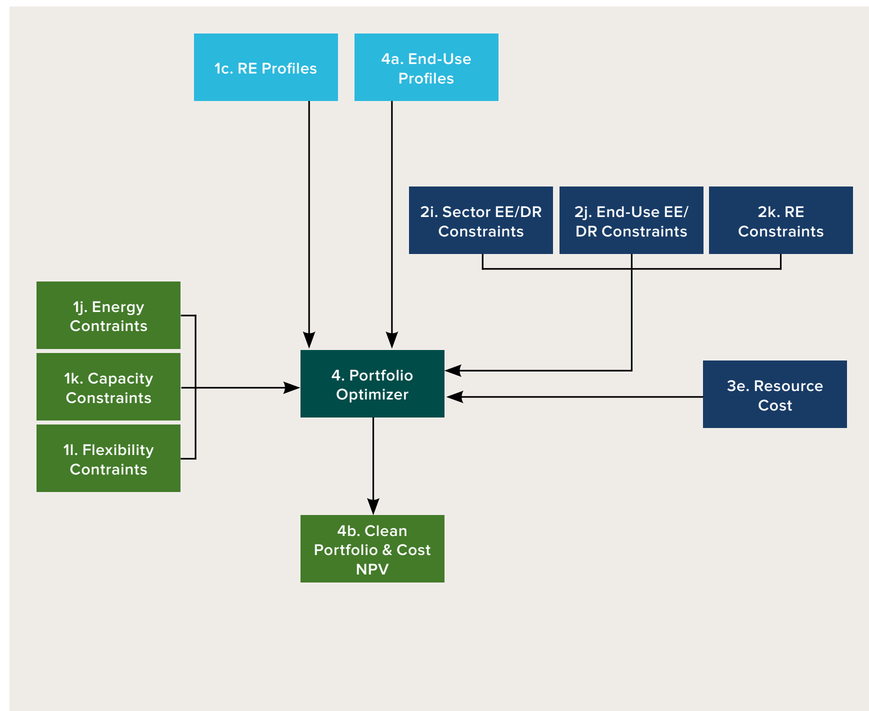
OUTPUTS

- MWs of each resource selected for the clean portfolio and the years they are built: (4b)
- Cost NPV of the clean portfolio: (4b)

Description: We use linear programming to select the portfolio of resources that can provide at least the same energy, capacity, and flexibility services as the BAU plant for the lowest cost. To do this, we use resource cost estimates from the resource cost assessment, service requirements from the service requirement model, and available resources from the resource potential assessment. These three elements form our linear program's objective function, and its two groups of constraints: service constraints and resource constraints. The objective function states, mathematically, what we are trying to achieve: the lowest-cost portfolio. The constraints state all requirements and limitations the portfolio must satisfy.

FIGURE C-10

PORTFOLIO OPTIMIZER SCHEMATIC



Valuing Additional Energy

- All of the portfolios produce more energy than the service requirement and their own DR and energy storage needs would consume; we call this quantity "additional energy." The value of this energy could vary significantly depending on the timing and system conditions under which it is produced, and we attempt to make a single generic assumption about the value of this energy to apply across all cases and report the total present cost of each clean portfolio, as well as a net total cost that accounts for the estimated value of this additional energy.

- The primary focus of this analysis is comparing costs to address service requirements, and valuing additional energy is a rough estimate of the value of exceeding the energy service requirement. We neglect the value of exceeding other service requirements.

- The amount of additional energy is calculated annually as the difference between energy generated by the clean portfolio and the energy generated by the BAU plant. From that number is subtracted the amount of energy shifted using demand response and energy storage, assuming an 86% battery efficiency.

- Additional energy is conservatively valued for each year by assuming that the marginal cost of an efficient combined cycle gas plant is what would be displaced by the additional energy production. We use the lower value of both heat rate and variable O&M from Lazard LCOE v11, i.e., 6133 Btu/kWh and $2/MWh, respectively. We inflate VOM using a 2% inflation rate. The gas price we use is 90% of the EIA Henry Hub price for the low-oil price case for the appropriate year from EIA's AEO 2017. This assumption serves as a rough average of the value of additional energy.

TABLE C-1

RESOURCE CONSTRAINTS

	LEFT-HAND SIDE	RIGHT-HAND SIDE	DETAILS
End-Use EE	Selected capacity of each EE end use	Estimated potential of each EE end use	The LP only allows 2-25% (depending on the case) of the end-use potentials from the resource potential assessment
End-Use DR	Selected capacity of each DR end use	Estimated potential of each DR end use	The LP only allows 2-25% (depending on the case) of the end-use potentials from the resource potential assessment
Sector EE	Annual energy savings from industrial, residential, and commercial	80% of sector estimates from the resource potential assessment	EPRI state-level efficiency economic potential for each sector as a % of state energy use is applied to gross energy projections to yield EE energy savings
Sector DR	Selected end-use peak-reduction totals for industrial/ commercial and residential	80% of sector estimates from the resource potential assessment	FERC state-level DR achievable participation for each sector as a % of state peak load is applied to gross load projections to yield DR peak reduction
RE Potential	Selected capacity of PV and wind	NREL state-level RE capacity potential	

TABLE C-2

SERVICE CONSTRAINTS

	LEFT-HAND SIDE	RIGHT-HAND SIDE	DETAILS
Monthly Energy	Wind, PV, and EE	Proposed power plant energy production based on net-load calculations and service requirement model	
Top 50 net-load hours / **Top 30 net-load hours**	Wind, PV, EE, ES, and DR	Proposed plant capacity (or in some cases, the capacity needed from the plant for a particular year)	A given DR resource can only be used two hours per day. ES has four hours of storage, but can spread that energy over more hours if they are among the top 50 hours
Flexibility (single-ramphour)	Wind, PV, EE, ES, and DR during largest one-hour increase in system net load	Proposed plant capacity (or in some cases, the capacity needed from the plant for a particular year)	This constraint is actually the highest of the top 50 hours discussed above, so the same issues apply
Flexibility (portfolio internal ramp)	Wind, PV, EE, ES, and DR	Fall in solar power output during its largest four-hour drop	ΔWind and ΔEE during solar's largest four-hour drop. The model looks at the worst drop for both fixed and tracking.

Clean portfolio LP mathematical formulation

The Clean Portfolio Linear Program takes the outputs of the service requirement model, the resource potential assessment, and the resource cost assessment, as well as additional case parameters, and selects the lowest-cost portfolio of resources that can provide at least the same energy, capacity, and flexibility services as that case's BAU plant. The following is a mathematical formulation of the Clean Portfolio Linear Program (LP).

As with all LPs, our LP formulation has an objective function and constraints, both of which are linear functions of the decision variables. We define 29 decision variables for each year and the number of MW of each type of resource, with up to five distinct years in the model. Note, these MW values represent nameplate capacity for renewable resources and energy storage, while for EE and DR they represent the MW reduction at the hour of highest demand for a given end use. The way we have structured, named, and indexed these decision variables carries through to other portions of the LP. Those conventions are described here, and used elsewhere in the methodology. The table below provides the names of the modeled resources that are represented by the decision variable $\mathbf{x}_y$, which is the vector for model year y.

Resource	Sub-Resource	# End Uses	Description
re_y	$\mathrm{re}_{y,pv}$	-	fixed-tilt PV
	$\mathrm{re}_{y,pvt}$	-	single-axis tracking PV
	$\mathrm{re}_{y,w}$	-	wind
es_y	$\mathrm{es}_{y,\mathrm{4h}}$	-	energy storage (4 hours)
	$\mathrm{es}_{y,\mathrm{6h}}$	-	energy storage (6 hours)
ee_y	$\mathrm{ee}_{y,ind}$	1	industrial EE
	$\mathrm{ee}_{y,res}$	5	residential EE
	$\mathrm{ee}_{y,com}$	6	commercial EE
dr_y	$\mathrm{dr}_{y,ind}$	1	industrial DR
	$\mathrm{dr}_{y,res}$	5	residential DR
	$\mathrm{dr}_{y,com}$	6	commercial DR

The 145-element vector of decision variables $\mathbf{x}$ is made up of the above sequence over the five elements of the model year index, y. Each element in this vector represents how many MW of that particular resource is selected by the model to be built in that particular year. The 145-element vector $\mathbf{c}$ of objective coefficients is constructed with the same structure as $\mathbf{x}$. Each element of $\mathbf{c}$ is the sum of CapEx and OpEx for one MW of the appropriate resource such that $c_{y,j} = k_{y,j} + o_{y,j}$ where $k_{y,j}$ is the CapEx for resource j in year y and $o_{y,j}$ is the OpEx for resource j put into service in year y. The objective function is defined as follows:

$$\text{minimize} \qquad z = \mathbf{c}^{\mathrm{T}}\mathbf{x} \tag{2.1}$$

As with standard LP convention, this minimization is subject to a set of linear constraints on the decision variables, $\mathbf{x}$. The formulation of these constraints is described below in greater detail, but all conform with a general format of:

$$\mathbf{A}_i\mathbf{x} \leq \mathbf{b}_i \tag{2.2}$$

Where the matrix $\mathbf{A}_i$ represents the coefficients on the decision variables, left-hand side (LHS) that translate $\mathbf{x}$ into the same units as a set of constant constraints, right-hand side (RHS). The actual constraints are defined by $\mathbf{b}_i$. For this generic formulation, i is used as a placeholder, and specific subscripts for each group of constraints are described below. Additionally, to simplify the formulation, let $\mathbf{1}$ and $\mathbf{0}$ be matrices in which all the elements are 1 or 0 respectively, and their dimensions are appropriate for the context in which they are invoked.

The first set of constraints sets the maximum amount of any individual resource that can can be built; this 29-element vector $\mathbf{max}$ is constructed exactly as $\mathbf{x}_y$. RE maxima are taken from NREL, ES is constrained at two times the capacity of the BAU plant, and EE and DR end-use maxima are taken from the outputs of the resource potential assessment. These maxima are assumed to be constant over all model years. This constraint can be written as follows:

$$\mathbf{A}_{max} = \begin{bmatrix} \mathbf{I} & \mathbf{I} & \mathbf{I} & \mathbf{I} & \mathbf{I} \end{bmatrix}; \qquad \mathbf{b}_{max} = \mathbf{max} \tag{2.3}$$

The second set of constraints limits the total savings from EE measures at the sector level for a particular year. These EE resource potential limits are taken from the outputs of the resource potential assessment. To calculate the energy saved by a MW of an EE end-use measure, the LP takes a 8,760×12 matrix of capacity factors, normalized to their respective max values for the appropriate case. This matrix is defined as $\mathbf{EU}$, and is adapted from *Reinventing Fire*. Each column is an end use, organized by sector, and each row is an hour of the year. The column sums of $\mathbf{EU}$ represent the total energy saved by one MW of EE of each end use. We define a vector, $\mathbf{eue}$, as $\mathbf{EU}^{\mathrm{T}} \times \mathbf{1} = \mathbf{eue}$, which represents the amount of energy saved during a year by one MW of an EE measure for the corresponding 12 end uses. This allows the definition of LHS matrix $\mathbf{A}_{\mathrm{ee}}$ for the sector-level EE constraints and the corresponding right-hand side vector $\mathbf{b}_{\mathrm{ee}}$ as follows:

$$\mathbf{A}_{\mathrm{ee}} = \begin{array}{c} \begin{matrix} \dots & \mathrm{ee}_{1,ind} & \mathrm{ee}_{1,res} & \mathrm{ee}_{1,com} & \dots & \mathrm{ee}_{5,ind} & \mathrm{ee}_{5,res} & \mathrm{ee}_{5,com} & \dots \end{matrix} \\ \begin{bmatrix} \dots & \mathbf{eue}_{ind}^{\mathrm{T}} & \mathbf{0} & \mathbf{0} & \dots & \mathbf{0} & \mathbf{0} & \mathbf{0} & \dots \\ \dots & \mathbf{0} & \mathbf{eue}_{res}^{\mathrm{T}} & \mathbf{0} & \dots & \mathbf{0} & \mathbf{0} & \mathbf{0} & \dots \\ \dots & \mathbf{0} & \mathbf{0} & \mathbf{eue}_{com}^{\mathrm{T}} & \dots & \mathbf{0} & \mathbf{0} & \mathbf{0} & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ \dots & \mathbf{eue}_{ind}^{\mathrm{T}} & \mathbf{0} & \mathbf{0} & \dots & \mathbf{eue}_{ind}^{\mathrm{T}} & \mathbf{0} & \mathbf{0} & \dots \\ \dots & \mathbf{0} & \mathbf{eue}_{res}^{\mathrm{T}} & \mathbf{0} & \dots & \mathbf{0} & \mathbf{eue}_{res}^{\mathrm{T}} & \mathbf{0} & \dots \\ \dots & \mathbf{0} & \mathbf{0} & \mathbf{eue}_{com}^{\mathrm{T}} & \dots & \mathbf{0} & \mathbf{0} & \mathbf{eue}_{com}^{\mathrm{T}} & \dots \end{bmatrix} \end{array} \tag{2.4}$$

$$\mathbf{b}_{\mathrm{ee}} = \begin{bmatrix} max\_ee_{1,ind} \\ max\_ee_{1,res} \\ max\_ee_{1,com} \\ \vdots \\ max\_ee_{5,ind} \\ max\_ee_{5,res} \\ max\_ee_{5,com} \end{bmatrix}$$

The sector-level DR constraints have a similar structure but, in their case, they constrain the cumulative amount of capacity installed, so we need not refer to the end-use capacity factors. The LHS matrix $\mathbf{A}_{\mathrm{dr}}$ for the sector-level DR constraints and the corresponding right hand-side vector $\mathbf{b}_{\mathrm{dr}}$ are defined as follows:

$$\mathbf{A}_{\mathrm{dr}} = \begin{array}{c} \begin{matrix} \dots & \mathrm{dr}_{1,ind} & \mathrm{dr}_{1,res} & \mathrm{dr}_{1,com} & \dots & \mathrm{dr}_{5,ind} & \mathrm{dr}_{5,res} & \mathrm{dr}_{5,com} \end{matrix} \\ \begin{bmatrix} \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{1} & \dots & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \dots & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{1} & \dots & \mathbf{1} & \mathbf{0} & \mathbf{1} \\ \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \dots & \mathbf{0} & \mathbf{1} & \mathbf{0} \end{bmatrix} \end{array} \tag{2.5}$$

$$\mathbf{b}_{\mathrm{dr}} = \begin{bmatrix} max\_dr_{1,ind/com} \\ max\_dr_{1,res} \\ \vdots \\ max\_dr_{5,ind/com} \\ max\_dr_{5,res} \end{bmatrix}$$

The fourth set of constraints requires that the Clean Portfolio provide at least the same amount of energy in each month of every model year as the BAU plant does in the service requirement model. For model year y, these monthly energy requirements are the 12 elements in the vector $\mathbf{en}_y$. To calculate the amount of energy saved by a MW of EE of a particular end use, let $\mathbf{L}$ be a 8,760×12 matrix in which each column represents a month and each row an hour, such that for any element $\ell_{h,g}$, if hour h is in month g, then $\ell_{h,g} = 1$, and otherwise $\ell_{h,g} = 0$. That allows the calculation of $\mathbf{EU}_\ell$ as $\mathbf{EU}^{\mathrm{T}}\mathbf{L} = \mathbf{EU}_\ell^{\mathrm{T}}$ in which the columns are the end uses and the rows are months. We perform a similar task to account for RE energy production, using a 8,760×3 matrix of regionally appropriate capacity factors $\mathbf{RE}$ adapted from *Reinventing Fire* in which the columns are the types of RE and the rows are the hours of the year. That allows the calculation of $\mathbf{RE}_\ell$ as $\mathbf{RE}^{\mathrm{T}}\mathbf{L} = \mathbf{RE}_\ell^{\mathrm{T}}$

in which the columns are the RE types and the rows are months.

$$
\mathbf{A}_{en} = \begin{array}{c} \begin{array}{cccccccc} \mathrm{re}_1 & \mathrm{es}_1 & \mathrm{ee}_1 & \dots & \mathrm{re}_5 & \mathrm{es}_5 & \mathrm{ee}_5 & \dots \end{array} \\ \begin{bmatrix} -\mathbf{RE}_\ell & \mathbf{0} & -\mathbf{EU}_\ell & \dots & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ -\mathbf{RE}_\ell & \mathbf{0} & -\mathbf{EU}_\ell & \dots & -\mathbf{RE}_\ell & \mathbf{0} & -\mathbf{EU}_\ell & \mathbf{0} \end{bmatrix} \end{array} \tag{2.6}
$$

$$
\mathbf{b}_{en} = \begin{bmatrix} -\mathbf{en}_1 \\ \vdots \\ -\mathbf{en}_5 \end{bmatrix}
$$

The fifth set of constraints requires that the Clean Portfolio provide capacity equal to or greater than the capacity of the BAU plant during the 50 hours of each model year with the highest system net load. There is no straightforward way to define these capacity constraints using algebra as there is for the previous sets of constraints. Instead (2.7) represents a generic set of rows of the capacity constraints' LHS matrix for the first model year, of which there are up to 50 (for each model year). For DR and ES there is an additional factor; ES can only provide capacity for a limited period of time—either four or six hours depending on the ES selected—and we assume that a given DR resource can only provide capacity for up to two hours per day. This requires that a figure for how many times a given day is represented in those top hours, for a given hour h in model year y that value is $d_{y,h}$, be entered into the model. Since a resource can never provide more capacity than its actual capacity, an additional row is required just in case

$2/d_{y,h} > 1$ or $4/d_{y,h} > 1$.

The rows for hour h of model year 1 are(4b) as follows:

$$
\mathbf{A}_{cap_{1,h}} = \begin{array}{c} \begin{array}{cccccc} \mathrm{re}_1 & \mathrm{es}_{1,4\mathrm{h}} & \mathrm{es}_{1,6\mathrm{h}} & \mathrm{ee}_1 & \mathrm{dr}_1 & \dots \end{array} \\ \begin{bmatrix} -\mathbf{re}_h & -\dfrac{4}{d_{1,h}} & -\dfrac{6}{d_{1,h}} & -\mathbf{eu}_h & -\dfrac{2}{d_{1,h}}\mathbf{eu}_h & \mathbf{0} \\ -\mathbf{re}_h & -1 & -1 & -\mathbf{eu}_h & -\mathbf{eu}_h & \mathbf{0} \end{bmatrix} \end{array} \tag{2.7}
$$

$$
\mathbf{b}_{cap_{1,h}} = \begin{bmatrix} -BAU\_cap \\ -BAU\_cap \end{bmatrix}
$$

Where $\mathbf{re}_h$ and $\mathbf{eu}_h$ are the h^{th} row of the $\mathbf{RE}$ and $\mathbf{EU}$ matrices respectively.

In addition to the hours described above, for each model year, the hour with the largest increase in system net load is also included in this list of hours, to which the above constraint is applied. Further, in cases where winter capacity is of specific interest, the 30 hours with the highest system net load during winter are also subjected to the above constraint.

The sixth set of constraints requires that the Clean Portfolio be able to meet the portfolio internal ramp, which we define as making up for the largest four-hour drop in both fixed- and single-axis tracking solar generation. The first hour of the drop in fixed solar is hour s, and the first hour of the drop in tracking solar is hour t. This flexibility constraint for model year 1 is then as follows:

$$
\mathbf{A}_{flex_1} = \begin{array}{c} \begin{array}{cccccccc} \mathrm{re}_{1,pv} & \mathrm{re}_{1,pvt} & \mathrm{re}_{1,w} & \mathrm{es}_{1,4\mathrm{h}} & \mathrm{es}_{1,6\mathrm{h}} & \mathrm{ee}_1 & \mathrm{dr}_1 & \dots \end{array} \\ \begin{bmatrix} re_{s,pv} - re_{s+4,pv} & 0 & re_{s+4,w} - re_{s,w} & 2 & 2 & \mathbf{eu}_{s+4} - \mathbf{eu}_s & \mathbf{eu}_{s+4} & \mathbf{0} \\ 0 & re_{t,pvt} - re_{t+4,pvt} & re_{t+4,w} - re_{t,w} & 2 & 2 & \mathbf{eu}_{t+4} - \mathbf{eu}_t & \mathbf{eu}_{t+4} & \mathbf{0} \end{bmatrix} \end{array} \tag{2.8}
$$

$$
\mathbf{b}_{flex_1} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}
$$

Having defined the LHS matrices $\mathbf{A}_i$ and RHS vectors $\mathbf{b}_i$ for each set of constraints i, it is now possible to write the Clean Portfolio LP in the standard LP format.

$$\begin{aligned} \text{minimize} \quad & z = \mathbf{c}^{\mathrm{T}}\mathbf{x} \\ \text{subject to} \quad & \begin{bmatrix} \mathbf{A}_{max} \\ \mathbf{A}_{\mathrm{ee}} \\ \mathbf{A}_{\mathrm{dr}} \\ \mathbf{A}_{en} \\ \mathbf{A}_{cap} \\ \mathbf{A}_{flex} \\ -\mathbf{I} \end{bmatrix} \mathbf{x} \leq \begin{bmatrix} \mathbf{b}_{max} \\ \mathbf{b}_{\mathrm{ee}} \\ \mathbf{b}_{\mathrm{dr}} \\ \mathbf{b}_{en} \\ \mathbf{b}_{cap} \\ \mathbf{b}_{flex} \\ \mathbf{0} \end{bmatrix} \end{aligned} \tag{2.9}$$

The final set of constraints is made up of nonnegativity constraints that assure that the LP never selects a negative capacity for any resource.

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