Changes in the Economic Value of Variable Generation with Increasing Penetration Levels: A Pilot Study of California

Andrew Mills and Ryan Wiser
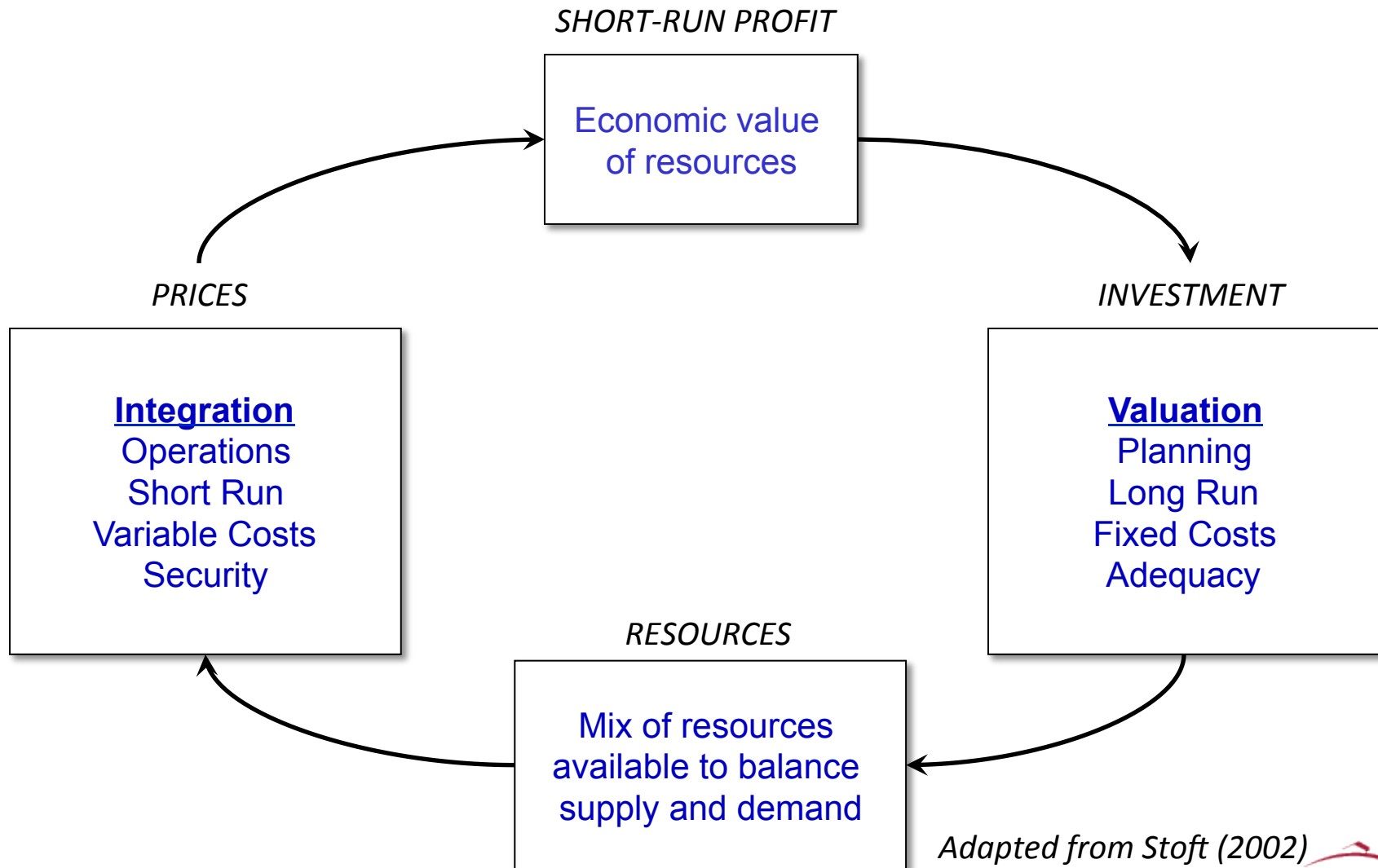Lawrence Berkeley National Laboratory

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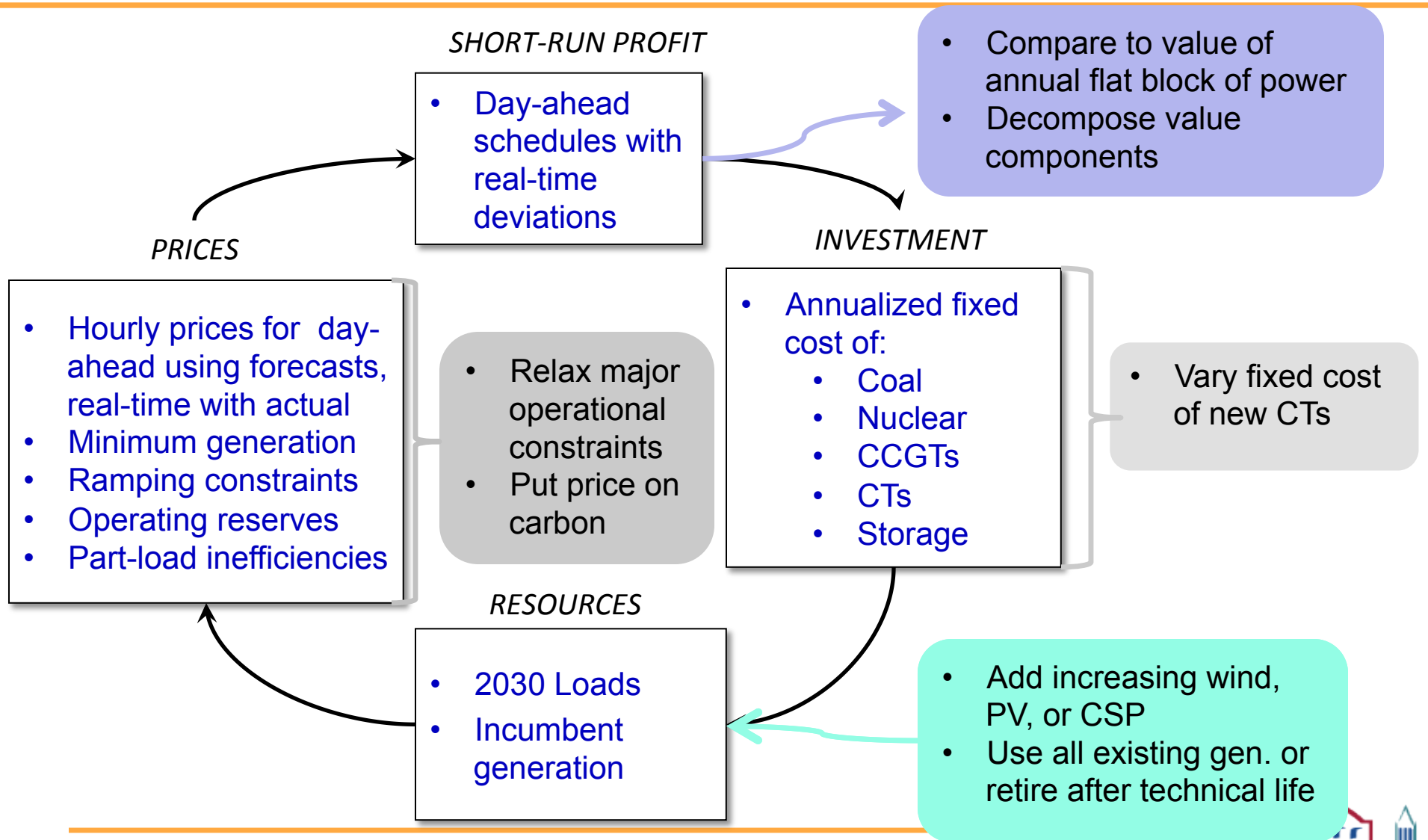**Environmental Energy Technologies Division • Energy Analysis Department**

Overview and motivation

- **Resource procurement and investment decisions are made more difficult by the variable and unpredictable nature of variable generation (VG)**

    - Simple comparisons of the levelized cost of energy (LCOE) between new generation options, for example, are insufficient to show relative economic attractiveness

    - Part of what is missing from simple comparisons is an evaluation of the economic value of the energy generated

- **Use a long-run modeling framework to evaluate economic benefits of several different VG technologies:**

    - Wind, single-axis tracking photovoltaics (PV), and concentrating solar power (CSP) with and without six hours of thermal energy storage (CSP_6 and CSP_0, respectively)

- **Include high time resolution (hourly over a full year) and incorporate operational constraints into long run valuation framework**

Long run investment framework

SHORT-RUN PROFIT

Economic value
of resources

PRICES

Integration
Operations
Short Run
Variable Costs
Security

INVESTMENT

Valuation
Planning
Long Run
Fixed Costs
Adequacy

RESOURCES

Mix of resources
available to balance
supply and demand

Adapted from Stoft (2002)

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Long run investment framework

SHORT-RUN PROFIT

- Day-ahead schedules with real-time deviations

- Compare to value of annual flat block of power
- Decompose value components

PRICES

- Hourly prices for day-ahead using forecasts, real-time with actual
- Minimum generation
- Ramping constraints
- Operating reserves
- Part-load inefficiencies

- Relax major operational constraints
- Put price on carbon

INVESTMENT

- Annualized fixed cost of:
  - Coal
  - Nuclear
  - CCGTs
  - CTs
  - Storage

- Vary fixed cost of new CTs

RESOURCES

- 2030 Loads
- Incumbent generation

- Add increasing wind, PV, or CSP
- Use all existing gen. or retire after technical life

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Pilot California case study: data and assumptions

- **Resources:**
  - Focus on California, 2030 hourly loads (2004 load shapes)
  - Solar PV and wind hourly actual and day-ahead forecast from WWSIS (2004 shapes)
  - Incumbent generation: retirement after technical life of 30 yr for CT/CCGT, 50 yr steam, 60 yr nuclear

- **Prices:**
  - Simplified commitment and dispatch based on 19 thermal plant vintages: linear on-line constraints rather than integer commitment.; forecasts are deterministic (not stochastic)
    - CSP commitment and dispatch is similar simplification of approach used by Sioshansi and Denholm (2010)
  - Hourly energy prices for day-ahead (DA) based on forecasts, real-time (RT) based on actual
  - Hourly ancillary services prices for regulation, spinning and non-spinning reserves
  - Reserve quantities based on rules-of-thumb developed in the WWSIS
  - "Energy only" market, meaning that capacity costs are covered through scarcity prices in energy market rather than side capacity payment

- **Short-run profits:**
  - Revenues based on DA schedule at DA prices, deviations at RT prices, and ancillary services costs/revenues
  - Short-run profit of generation reflects the marginal economic value of adding an additional unit of energy with the same production profile

Primary caveats

- **Narrow definition of economic value:**
  - Avoided capital investment cost and variable fuel and O&M costs from other power plants in CA

- **Focus on California without evaluation of transmission:**
  - Renewable electricity only used to meet CA demand
  - Incumbent generation only includes generation in the CA NERC sub-region

- **Marginal economic value instead of average value:**
  - Only indicates value of next increment of VG

- **Simplified commitment and dispatch decisions:**
  - Vintages rather than individual unit commitment

In long run equilibrium, short-run profit of new plants equals annualized fixed costs
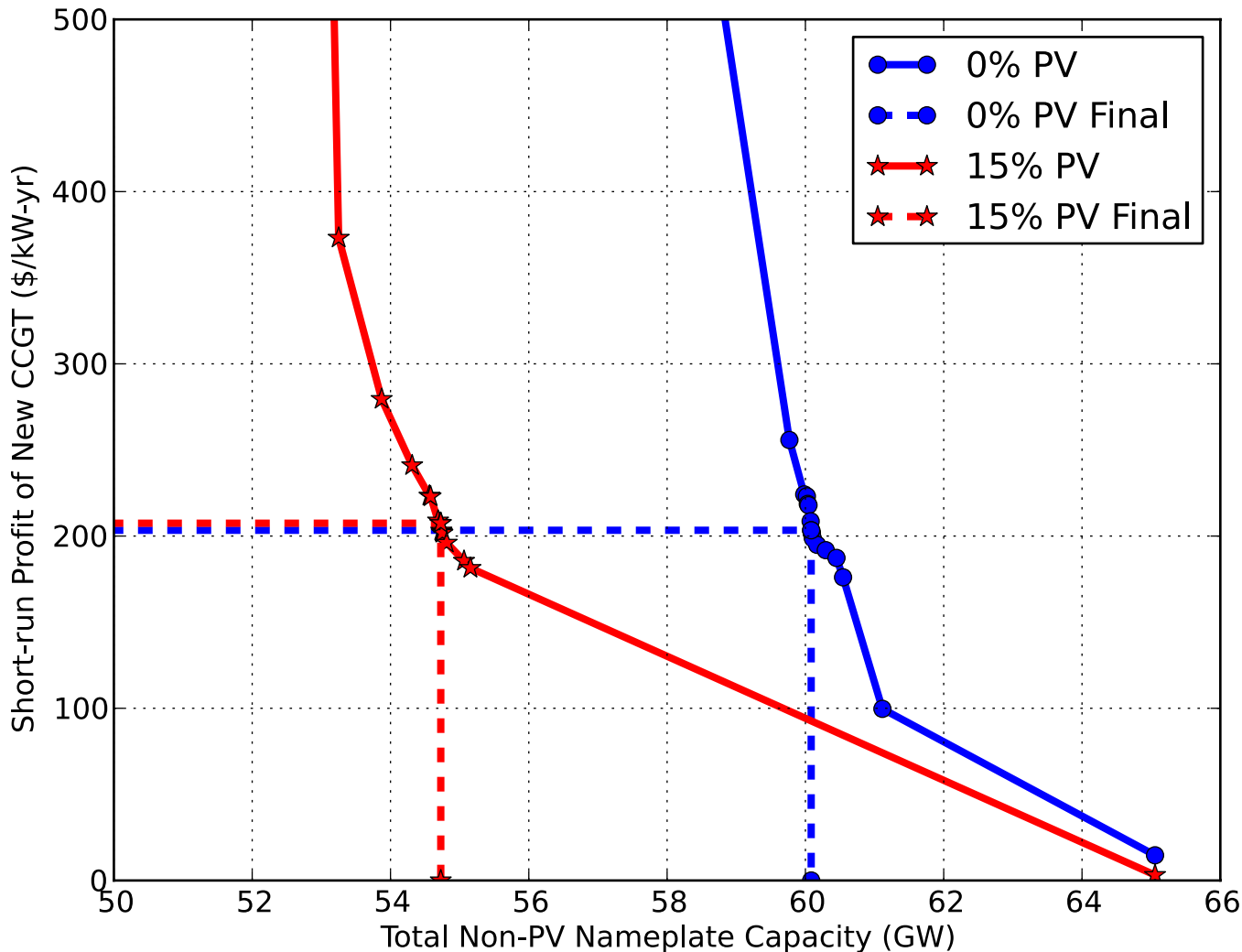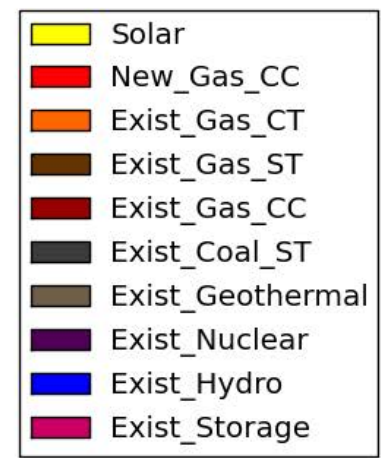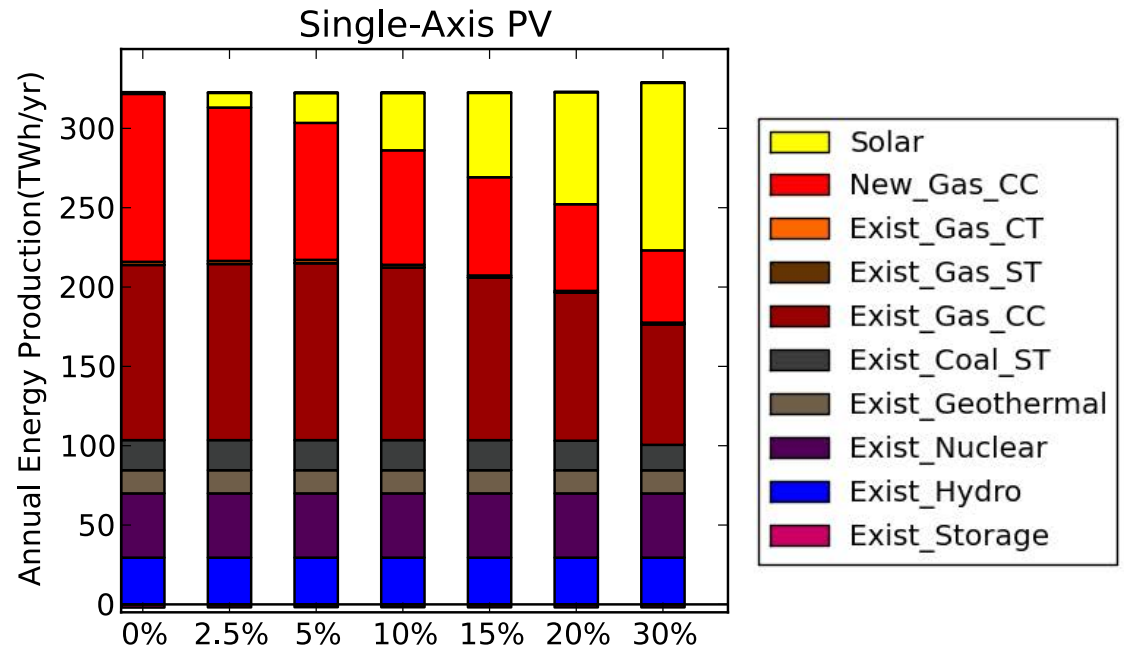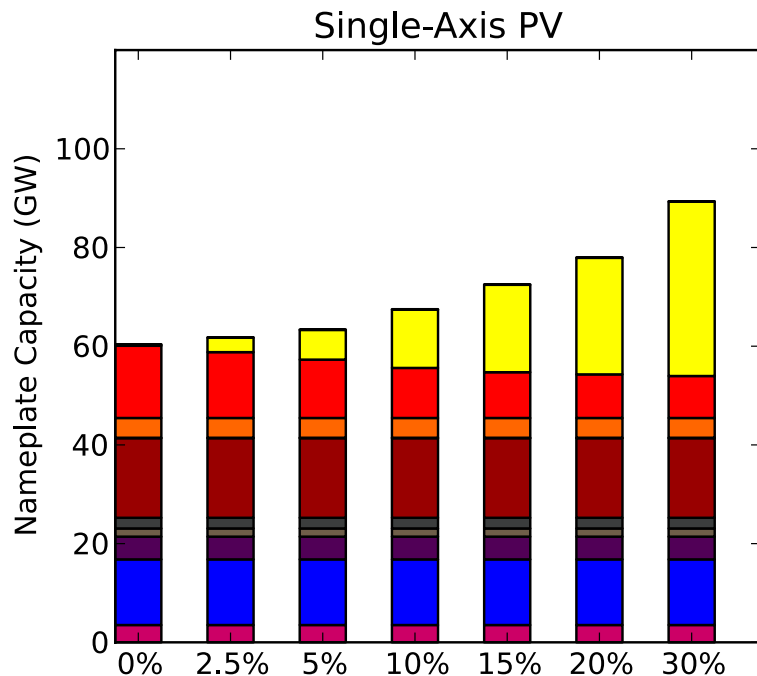

Investment model iterates through several candidate portfolios of generation capacity.

Total annualized fixed cost of a new combined cycle plant is assumed to be $203/kW-yr

Since new CCGTs are included in final iteration: short-run profit of CCGTs equals annualized fixed cost of CCGTs

# Investment and dispatch decisions with increasing PV penetration

Single-Axis PV — Nameplate Capacity (GW) vs PV Penetration (0%, 2.5%, 5%, 10%, 15%, 20%, 30%)

Single-Axis PV — Annual Energy Production (TWh/yr) vs PV Penetration (0%, 2.5%, 5%, 10%, 15%, 20%, 30%)

Legend: Solar, New_Gas_CC, Exist_Gas_CT, Exist_Gas_ST, Exist_Gas_CC, Exist_Coal_ST, Exist_Geothermal, Exist_Nuclear, Exist_Hydro, Exist_Storage

PV Penetration	Incremental Reduction in Non-PV Capacity (GW)	Incremental Increase in Nameplate PV (GW)	Effective Marginal Capacity Credit (%)
0% -> 5%	2.8	5.8	48%
15% -> 20%	0.4	5.9	7%

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Summary of investment and dispatch decisions with increasing VG penetration

- **Total nameplate capacity of VG and non-VG resources increases with increasing VG penetration**

  - Implied capacity credit is less than that of a conventional plant for all VG

  - Capacity credit is highest for CSP_6 at both low and high penetration levels and for PV and CSP_0 at low penetration

- **Energy from VG primarily displaces energy from CCGTs**

  - Leads to large reduction in capacity factor of CCGTs

  - Load factor of CCGTs also decreases, but decrease is moderated by fact that CCGTs can be brought offline

  - Overall only a modest reduction in CCGT efficiency with increasing wind, PV and CSP_0 penetration

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Marginal value of variable generation varies with technology and penetration
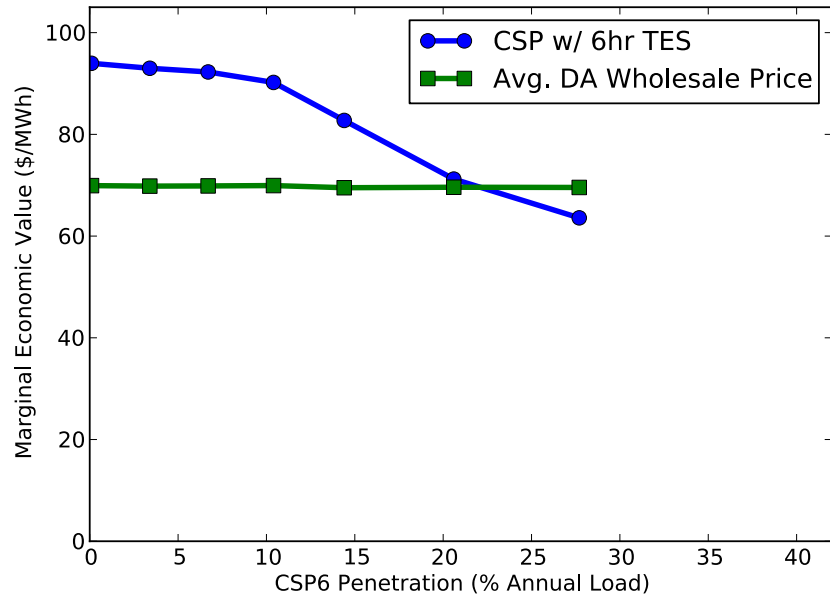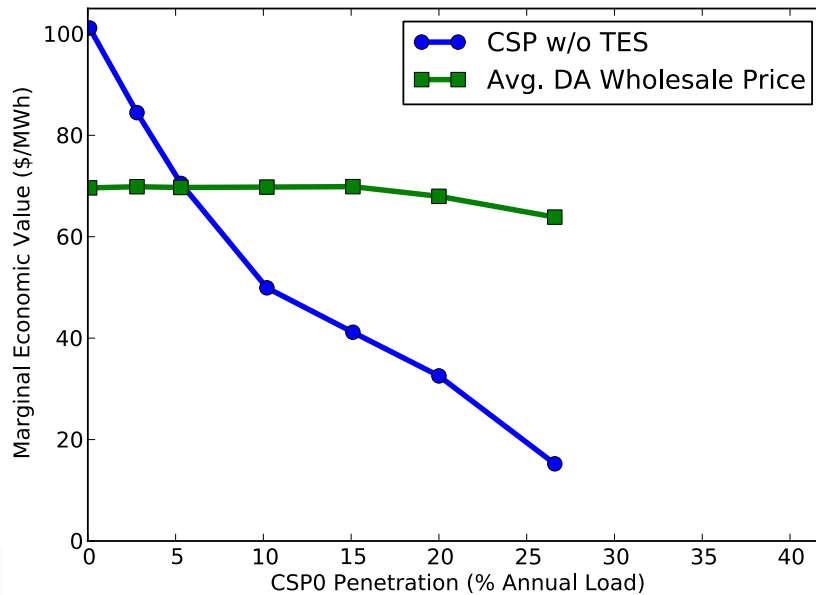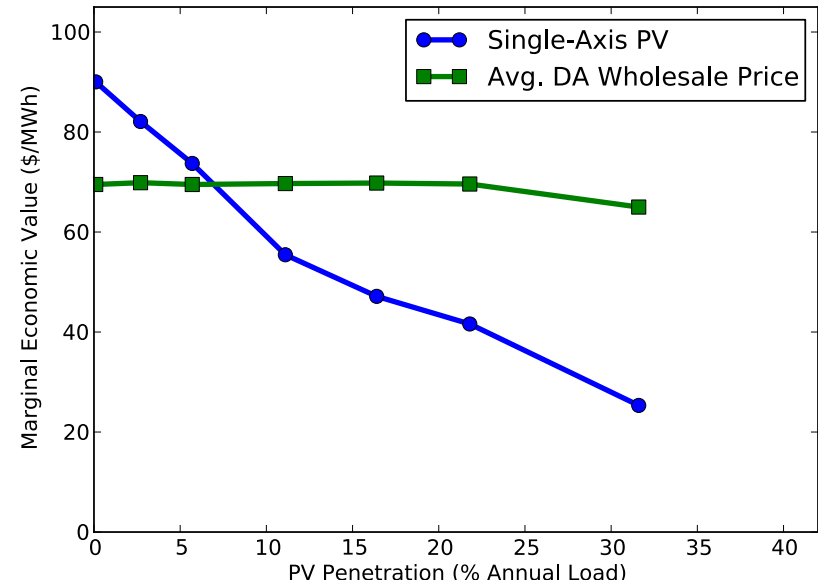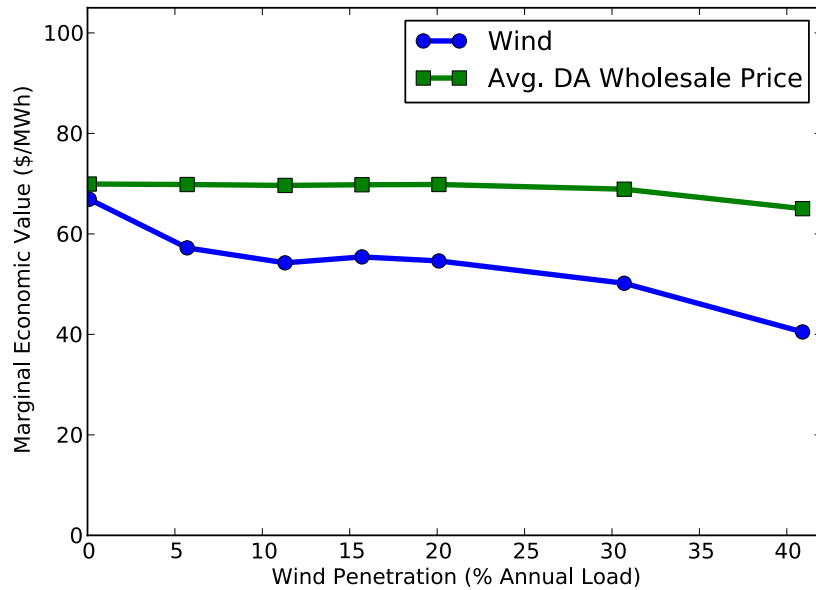
Decomposition of marginal economic value into additive components

- **Capacity value ($/MWh):**
  - Portion of short-run profit earned during hours with scarcity prices (defined to be greater than $500/MWh)

- **Energy value ($/MWh):**
  - Portion of short-run profit earned in hours without scarcity prices if DA forecast exactly matches RT generation

- **DA Forecast Error Cost ($/MWh):**
  - The net earnings from RT deviations from the DA schedule

- **Ancillary Services Cost ($/MWh):**
  - The net earnings from selling AS and/or paying for increased AS in the case of variable generation

Marginal value of a flat block of power changes only at very high penetration

Component ($/MWh)	0% Flat	5% Flat	10% Flat	15% Flat	20% Flat	30% Flat	40% Flat
+ Capacity Value (Capacity Value in $/kW-yr)	+20 (170)	+20 (180)	+20 (170)	+20 (180)	+20 (180)	+20 (180)	+16 (140)
+ Energy Value	+50	+50	+50	+50	+50	+50	+49
+ DA Forecast Error	0	0	0	0	0	0	0
+ Ancillary Services	0	0	0	0	0	0	0
= Marginal Economic Value	70	70	70	70	70	70	65

Marginal value of wind is largely driven by energy value

Component ($/MWh)	0% Wind	5% Wind	10% Wind	15% Wind	20% Wind	30% Wind	40% Wind
+ Capacity Value (Capacity Value in $/kW-yr)	+17 (69)	+12 (37)	+10 (30)	+10 (30)	+9 (28)	+8 (25)	+8 (25)
+ Energy Value	+50	+49	+48	+48	+48	+46	+39
+ DA Forecast Error	*-0.2*	*-3*	*-4*	*-2*	*-2*	*-3*	*-6*
+ Ancillary Services	*-0.4*	*-0.2*	*-0.2*	*-0.2*	*-0.2*	*-0.2*	*-0.2*
= Marginal Economic Value	67	57	54	55	54	50	40

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Marginal value of PV is high at low penetration due to high capacity value

Component ($/MWh)	0% PV	2.5% PV	5% PV	10% PV	15% PV	20% PV	30% PV
+ Capacity Value (Capacity Value in $/kW-yr)	+37 (120)	+34 (110)	+27 (82)	+13 (39)	+8 (24)	+4 (11)	+1 (4)
+ Energy Value	+54	+53	+52	+49	+45	+41	+27
+ DA Forecast Error	*-0.4*	*-5*	*-4*	*-6*	*-5*	*-4*	*-3*
+ Ancillary Services	*-0.9*	*-0.8*	*-0.7*	*-0.4*	*-0.2*	*-0.1*	*-0.0*
= Marginal Economic Value	90	81	73	55	47	41	25

Single-axis PV and CSP without TES have similar relative magnitude of different components and similar changes in value of components with increasing penetration.

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Marginal value of CSP with TES retains high level with higher penetration

| Component ($/MWh)	0% CSP_6	2.5% CSP_6	5% CSP_6	10% CSP_6	15% CSP_6	20% CSP_6	30% CSP_6
+ Capacity Value (Capacity Value in $/kW-yr)	+37 (150)	+37 (160)	+37 (150)	+35 (150)	+24 (100)	+20 (85)	+15 (61)
+ Energy Value	+55	+55	+55	+55	+58	+53	+52
+ DA Forecast Error	*-0.1*	*-1*	*-1*	*-1*	*-1*	*-2*	*-3*
+ Ancillary Services	+1.4	+1.4	+1.3	+1.2	+1.0	+0.7	+0.1
= Marginal Economic Value	94	93	92	90	83	71	64

Times with high net load and high prices shift to early evening with increasing PV
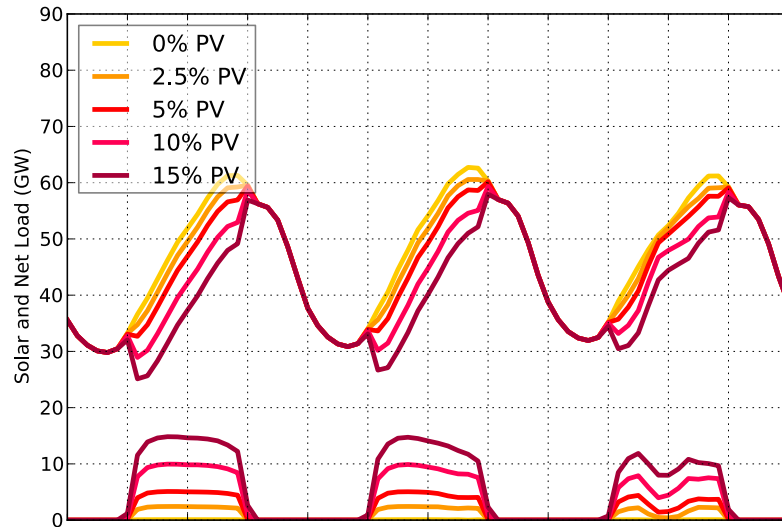
Highest load hours are occur in late afternoon.

With high PV penetration, highest net-load hours occur in the early evening.

PV does not generate in early evening hours
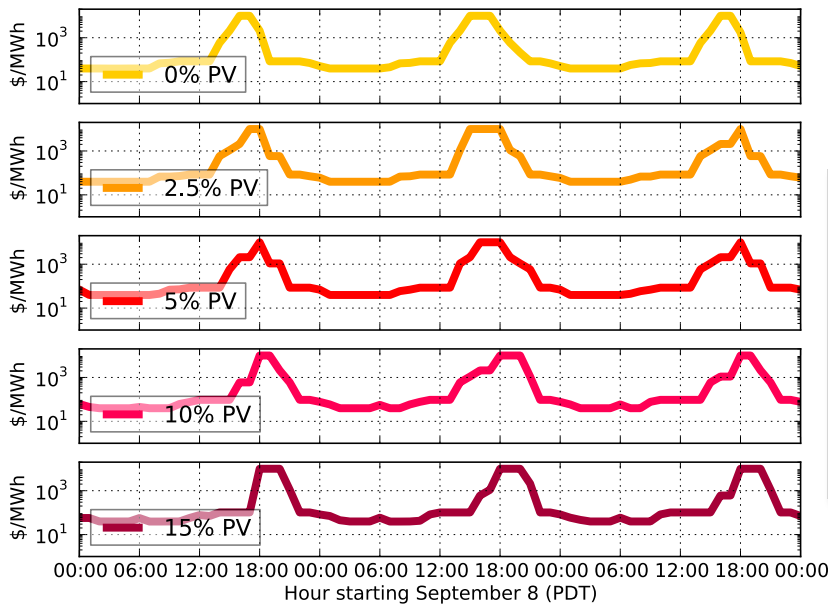
High price periods shift from times with **high load** to times with **high net-load**

Contribution of high price hours to marginal economic value of PV declines with high PV penetration
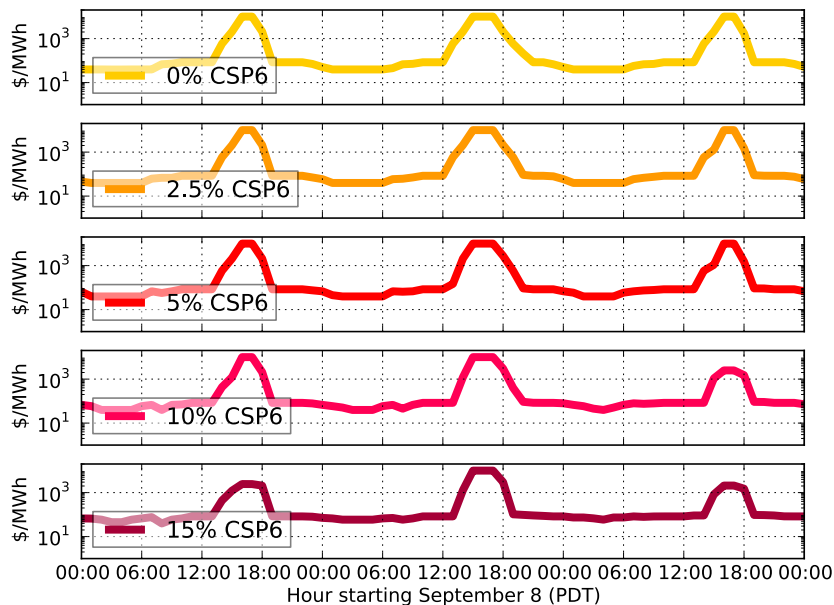
Times with high net load remain similar with modest penetration of CSP6
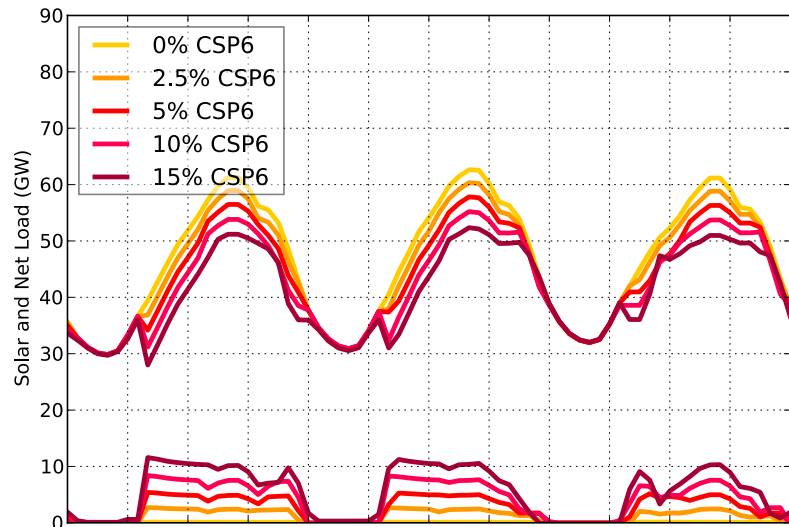
Highest load hours are occur in late afternoon.

With CSP_6, highest net-load hours remain in the late afternoon.

CSP_6 extracts energy from thermal storage starting in the early evening.

High price periods remain in the late afternoon even with increasing CSP_6 penetration

Contribution of high price hours to marginal economic value of CSP_6 remains relatively high even at 15% penetration

Sensitivity scenarios demonstrate marginal value depends on assumptions

- **Remove major operational constraints in dispatch model:**
  - Energy value of PV and CSP0 particularly increase at high penetration relative to reference scenario

- **Increase cost of energy with a $32/tonne CO_2 price:**
  - Energy value of all VG resources increases by $10-13/MWh up to 20% penetration

- **Reduce the cost of capacity from conventional plants:**
  - Lowers the capacity value but increases the energy value due to new CTs displacing more-efficient new CCGTs

- **Assume no existing plants retire for technical reasons:**
  - Increases amount of low-efficiency natural gas plants, decreases capacity value and increases energy value

Conclusions

- **Solar has high value at low penetration levels**
  - The high value is largely due to the high capacity value at low penetration
- **There is little apparent value to thermal storage for CSP plants at low penetration levels**
- **The value of PV and CSP without thermal storage drop considerably with increasing penetration levels**
  - Main driver is change in capacity value and energy value with increasing penetration
  - Day ahead forecast error and ancillary service costs do not change nearly as much with increasing penetration

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Conclusions (con't)

- **At medium to high penetration CSP with thermal storage is considerably more valuable relative to PV and CSP without thermal storage**

- **The value of wind is largely driven by energy value and is lower than solar at low penetration**

  - Largely because the capacity value of wind is lower than that of solar at low penetration

- **At high penetration, the value of wind can exceed the value of PV and CSP without thermal storage**

  - The capacity value is relatively stable and the energy value does not drop as fast as the energy value of PV and CSP without thermal storage

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Recommended Further Research

- **Impact of mitigation strategies on the value of variable generation at high penetration levels**

  - Combinations of VG, flexible conventional generation, demand response, low-cost bulk power storage, etc.

- **Capacity credit of solar at low penetration; how capacity credit changes with increasing penetration**

  - Capacity credit of CSP with thermal storage may need to be based on methods suited to evaluating adequacy in energy-constrained systems

- **Variation in value for different regional characteristics:**

  - Demand profile, incumbent generation, renewable resource options

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For More Information

Download the full report:

    http://eetd.lbl.gov/ea/EMS/re-pubs.html

Listen to a webinar presentation:

    http://westgov.adobeconnect.com/p2bc7cavm3e/

Contact info:

    Andrew Mills, ADMills@lbl.gov, (510) 486-4059

    Ryan Wiser, RHWiser@lbl.gov, (510) 486-5474