# Energy transition with variable and intermittent renewable electricity generation

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# Motivation: Integrating RE is a challenge (1)

- Renewable energies are obvious candidates to replace fossil fuels in electricity generation.
- Challenges associated with a higher penetration of RE:
  - cost,
  - variability (predictable): night and day, seasons,
  - intermittency (unpredictable): cloud cover...
  - space.

# Motivation: Integrating RE is a challenge (2)

- Cost issue: largely solved, due to technical progress and learning effects in production and installation.
  - Solar PV costs reduced by 20% for each doubling of the cumulative installed capacity (IEA, 2011). PVcost
  - US average LCOE for new generation resources, in 2017 $/MWh: 48.1 for natural gas CC, 90.1 for nuclear, 37 for wind onshore, 106.2 for wind offshore, 46.5 for solar PV (EIA, 2018). LCOE
- Variability and intermittency issues: not satisfactorily solved yet. Potential solutions:
  - backup of renewable sources by fossil fuel-fired power plants,
  - diversification of sources and dense transmission network,
  - storage (hydro-pumped storage, batteries, hydrogen production),
  - demand-side management.

# Related literature

1. Energy transition in macro-dynamic models à la Hotelling. The issue is the cost.
2. Design of the electricity mix under intermittency in static models (Ambec and Crampes, 2012, 2015):
    - Static models not interested in energy transition.
    - Study the optimal electricity mix with intermittent renewable sources, with and without storage.
    - Contrast it to the mix chosen by agents in a decentralized economy (retailing price of electricity does not vary with its availability).
    - Evaluate different public policies and their impacts on renewable penetration in the electric mix.

# What we do: Accounting for variability and intermittency in a macro-dynamic model (1)

- We build a stylized dynamic model of the optimal choice of the electricity mix, where:
  - abundant but $CO_2$-emitting fossil energy (coal),
  - variable and intermittent but clean renewable energy (solar),
  - carbon budget,
  - costly storage devices.
- We study the consequences of variability and intermittency for:
  - electricity consumption,
  - fossil fuel use,
  - accumulation of solar panels,
  - use of storage devices.
- We provide answers to important questions:
  - Are the effects of intermittency of second order compared to those of variability? Can they be safely ignored?
  - What is the value of storage?

# What we do: Accounting for variability and intermittency in a macro-dynamic model (2)

Main assumptions:

- To take into account intra-day variability, electricity produced when there is sun and when there is no sun are considered two different goods: day-electricity and night-electricity.
- Day-electricity produced with coal and/or solar.
- Night-electricity produced with coal or by the release of day-electricity that has been stored.
- Storing energy is costly: loss of energy during the restoration process.
- Coal and solar available at zero variable costs.
- Coal-fired power plants already exist (no capacity constraint).
- Initial solar capacity small (=0), so that investments are to be made to build up solar capacity.

# What we do: Accounting for variability and intermittency in a macro-dynamic model (3)

1. Variability only:
   - We study the timing of the use of coal, solar, and storage, and derive an optimal succession of regimes.
   - We derive the time profile of the carbon value and the shadow value of solar panels, and the optimal accumulation of panels, and the electricity price and consumption paths.
   - We perform comparative statics exercises using simulations:
     - improvements in the storage and solar power generation technologies,
     - more stringent environmental policy,
     - coincidence (or not) of sun and electricity demand (sun at peak or off peak).
2. Adding intermittency:
   - We perform the same type of analysis.
   - We show that the optimal solution is very different when the cloud problem is not too serious and when it is severe (i.e. in sunny and dry countries vs rainy countries).
   - We compute the value of storage.

$$\max \int_0^\infty e^{-\rho t} \left( \boxed{u\left(e_d(t), e_n(t)\right)} - C(I(t)) \right) dt$$

$$\boxed{\begin{aligned} e_d(t) &= x_d(t) + (1 - a(t))\overline{\phi} Y(t) \\ e_n(t) &= x_n(t) + k a(t) \overline{\phi} Y(t) \end{aligned}}$$

$$\begin{aligned} &\dot{X}(t) = x_d(t) + x_n(t) \\ &\dot{Y}(t) = I(t) \\ &x_d(t) \geq 0, \quad x_n(t) \geq 0, \quad 0 \leq a(t) \leq 1 \\ &X(t) \leq \overline{X} \\ &\quad X_0 \geq 0, \;\; Y_0 \geq 0 \text{ given} \end{aligned}$$

Specifications:

$$u\left(e_d, e_n\right) = \alpha \ln e_d + (1 - \alpha) \ln e_n, \qquad 0 < \alpha < 1$$

$$C(I) = c_1 I + \frac{c_2}{2} I^2, \qquad c_1, c_2 > 0$$

- Under the assumption $Y_0 = 0$, investment in solar panels takes place continuously, to increase capacity, up to a steady state $Y^* = 1/(\rho c_1)$.
- The optimal solution consists in 4 phases:
  1. production of day and night-electricity with coal complemented at day by solar, no storage (from 0 to $\underline{T}$);
  2. production of day-electricity with solar only, use of coal at night, no storage (from $\underline{T}$ to $T_i$);
  3. production of day-electricity with solar only, use of coal at night, progressive increase of storage from 0 to its maximal value, which depends on preferences for day and night-electricity (from $T_i$ to $\overline{T}$);
  4. production of day and night-electricity with solar only, storage at its maximum value, (from $\overline{T}$ to $\infty$). This last phase begins when the carbon budget is exhausted.

# Variability only: comparative statics

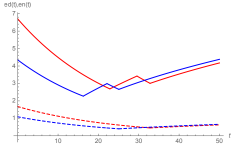
## Parameters

Parameters in the reference simulation, variability only:

| $\rho$ | $k$ | $\alpha$ | $\overline{\phi}$ | $c_1$ | $c_2$ | $Y_0$ | $X_0$ | $\overline{X}$ |
|---|---|---|---|---|---|---|---|---|
| 0.04 | 0.6 | 0.8 | 0.76 | 1 | 20 | 0 | 0 | 50 |

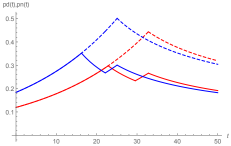
# Variability only: comparative statics

## Effect of a less stringent climate policy



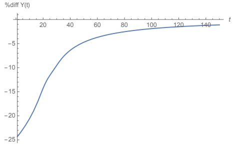

Energy consumption

day (plain) and night (dashed)



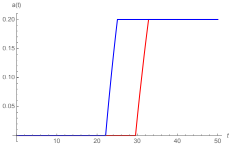

Price

day (plain) and night (dashed)




Solar capacity

(% diff.)



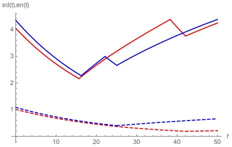

Storage

$\overline{X} = 50$ in blue, $\overline{X} = 100$ in red

- In the short run, energy consumptions at day and night are higher than in the reference case, prices are lower.
- Storage occurs later.
- The switch to clean energy is postponed.
- Investment in solar panels is lower, therefore solar capacity is smaller at each date. Hysteresis effect.
- Therefore in the medium run prices become higher and energy consumption lower than in the reference case.

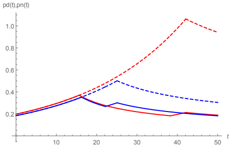
# Variability only: comparative statics

## Effect of a less efficient storage technology



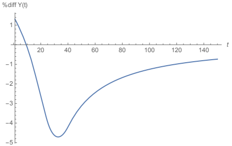

Energy consumption

day (plain) and night (dashed)



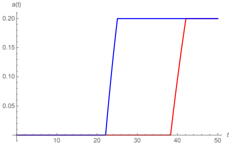

Price

day (plain) and night (dashed)




Solar capacity

(% diff.)



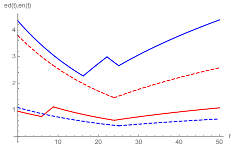

Storage

$k = 0.6$ in blue, $k = 0.2$ in red

- Detrimental to night-electricity consumption and price.
- The date at which storage begins is postponed.
- It allows to consume more at day in phase (2) at the expense of a smaller night-electricity consumption.

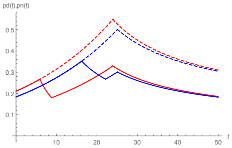
# Variability only: comparative statics

## Effect of a smaller preference for day-electricity, i.e. of off-peak sun



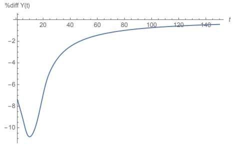

Energy consumption

day (plain) and night (dashed)



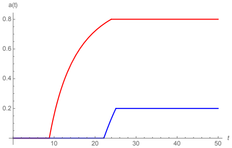

Price

day (plain) and night (dashed)




Solar capacity

(% diff.)



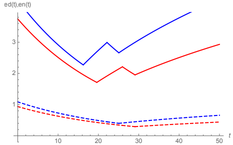

Storage

$\alpha = 0.8$ in blue, $\alpha = 0.2$ in red

- Off-peak sun: see the Californian duck case. duck
- The situation is worse in all respects.
- At each date, total electricity consumption (over day and night) is reduced.
- The date at which fossil is not used at day anymore is brought forward so that fossil consumption at night may be higher, and storage occurs earlier.
- The long run level of storage has to be higher, which means more overall electricity loss.
- Solar panel accumulation is delayed.

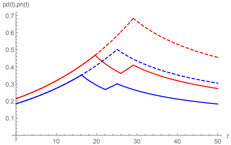
# Variability only: comparative statics

## Effect of less efficient solar electricity generation




Energy consumption

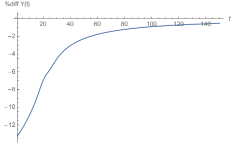
day (plain) and night (dashed)




Price

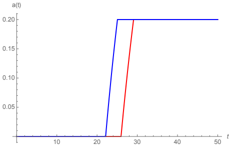
day (plain) and night (dashed)

$\overline{\phi} = 0.76$ in blue, $\overline{\phi} = 0.52$ in red




Solar capacity

(% diff.)




Storage

- At any time, energy consumptions at day and night are lower and prices are higher.
- Investment in solar panels is lower and storage is delayed, which postpones the switch to clean energy.

# The optimal solution with variability and intermittency

## The social planner's programme

$$\max \int_0^\infty e^{-\rho t} \left( \boxed{qu\left(e_d^u(t), e_n^u(t)\right) + (1-q)u\left(e_d^l(t), e_n^l(t)\right)} - C(I(t))\right) dt$$

$$\boxed{\begin{aligned} e_d^u(t) &= x_d(t) + (1-a(t))Y(t) \\ e_n^u(t) &= x_n(t) + ka(t)Y(t) \\ e_d^l(t) &= x_d(t) + (1-a(t))\phi Y(t) \\ e_n^l(t) &= x_n(t) + ka(t)\phi Y(t) \end{aligned}}$$

$$\begin{aligned} &\dot{X}(t) = x_d(t) + x_n(t) \\ &\dot{Y}(t) = I(t) \\ &x_d(t) \geq 0, \quad x_n(t) \geq 0, \quad 0 \leq a(t) \leq 1 \\ &X(t) \leq \overline{X} \\ &\quad X_0 \geq 0, \;\; Y_0 \geq 0 \text{ given} \end{aligned}$$

# The optimal solution with variability and intermittency

## Two different types of solutions (1)

1. $\phi > \tilde{\phi}$ (not too serious cloud problem): optimal solution when intermittency is taken into account close to when it is not. Same succession of phases.
2. $\phi < \tilde{\phi}$ (severe cloud problem): very different solution. Reluctance of the planner to abandon fossil at day in case of the occurrence of the bad event. Now storage begins optimally before fossil has been abandoned at day.
3. $\tilde{\phi}$ is the real positive and smaller than 1 solution of:

$$\phi^2 + \frac{k\left(q^2 + (1-q)^2\right) - 1}{kq(1-q)}\phi + 1 = 0$$

It is is an increasing function of $k$ : the more efficient the storage technology is, the smaller is the range of $\phi$s for which intermittency may be safely ignored.

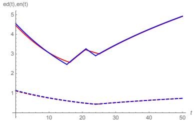
# The optimal solution with variability and intermittency
## Two different types of solutions (2)

Intuition:

- 2 methods to satisfy night-electricity demand under the climate constraint:
  1. abandon fossil at day to "save" fossil for night when solar capacity is high enough for day-electricity needs to be satisfied;
  2. transfer solar electricity from day to night through storage, at the expense of a loss.
- Variability only, and "not too bad" intermittency: begin storage when fossil has been abandoned at day and solar capacity is high enough, to avoid incurring the loss.
- "Bad" intermittency: abandon fossil at day later, to make sure than in the case of no or few sun day-electricity consumption can be satisfied, and store a part of solar day-electricity production to compensate for the smaller quantity of fossil left available for night.

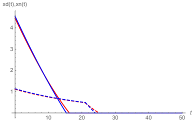
  Precautionary behaviour

# What taking intermittency into account changes when $\phi$ is high



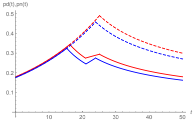

Expected energy consumption

day (plain) and night (dashed)

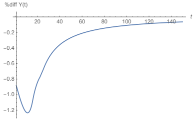



Fossil fuel consumption

day (plain) and night (dashed)

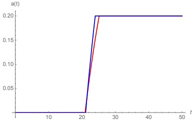



Expected day (plain) and night (dashed) price




Solar capacity

(% diff.)

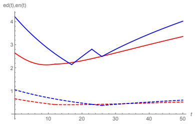



Storage

Variability only in blue, variability and intermittency with $\phi = 0.5$ in red

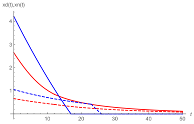
- The mistake on fossil fuel consumption and on storage and accumulation of solar panels policies the planner makes when he does not take into account intermittency is negligible.
- However he underestimates significantly the expected day and night-electricity price in the medium run.
- Welfare loss due to intermittency: 4.5%.
- See Gowrisankaran and Reynolds JPE 2016.

# What taking intermittency into account changes when $\phi = 0$



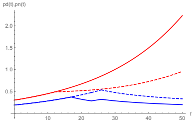

Expected energy consumption

day (plain) and night (dashed)

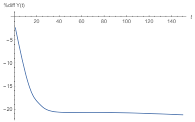



Fossil fuel consumption

day (plain) and night (dashed)

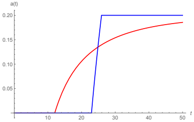



Expected day (plain) and night (dashed) price




Solar capacity

(% diff.)

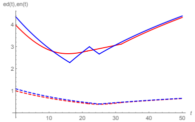



Storage

Variability only in blue, variability and intermittency with $\phi = 0$ in red

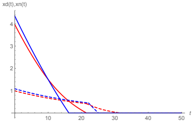
- Fossil and total electricity consumption are smaller in the short run. Precautionary behaviour.
- The switch to clean energy is postponed indefinitely.
- Storage begins much earlier.
- Solar capacity is much smaller. At the steady state, $Y^q = \frac{q}{\rho c_1} < Y^* = \frac{1}{\rho c_1}$.
- Welfare loss due to intermittency: 92.6%.
- Now the planner makes a big mistake if he does not take into account intermittency.

# What taking intermittency into account changes when $\phi = \tilde{\phi}$



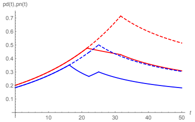

Expected energy consumption

day (plain) and night (dashed)

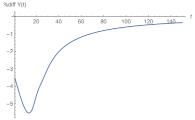



Fossil fuel consumption

day (plain) and night (dashed)

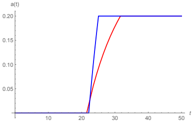



Expected day (plain) and night (dashed) price




Solar capacity

(% diff.)




Storage

Variability only in blue, variability and intermittency with $\phi = \tilde{\phi}$ in red

- Cutoff between the two types of solutions.
- Fossil consumption and expected energy consumption paths close to the ones with variability only.
- But welfare loss due to intermittency: 21.5%.

# The value of storage

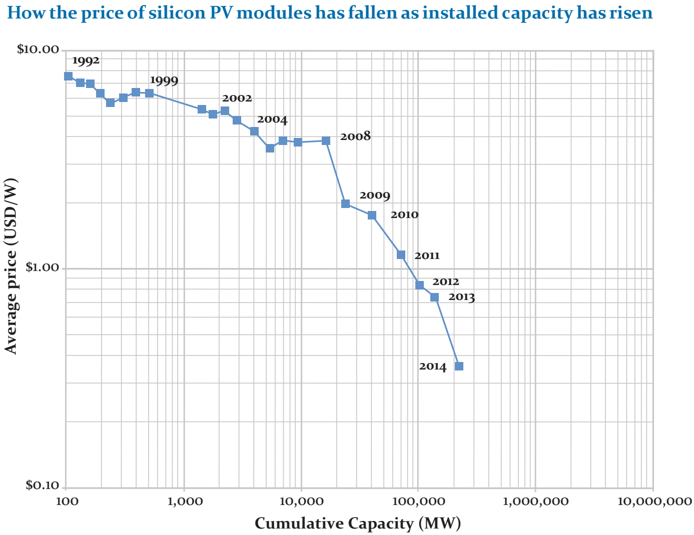
- Comparison of the general model with variability, intermittency and storage with a model with variability, intermittency but no storage technology.
- Only two phases appear when $0 < \phi < 1$.
  - Phase (1): fossil fuel is used night and day;
  - Phase (2): fossil fuel is used only during the night.
- Steady state: $Y^{**} = \frac{\alpha}{\rho c_1} < Y^{*} = \frac{1}{\rho c_1}$. Less accumulation of solar panels. Solar panels and storage are complements.
- Value of storage: the welfare loss when no storage technology is available is:
  - 19% for $\phi = 1$ (variability only),
  - 21% for $\phi = 0.5$,
  - 26% for $\phi = \tilde{\phi} = 0.2011$,
  - 212% for $\phi = 0$.

# Extensions

- This work can be considered as a first step in the study of energy transition under variability and intermittency of the clean sources.

- Next step on the agenda: decentralized version of the model, to study the design of policy instruments.

# PV cost



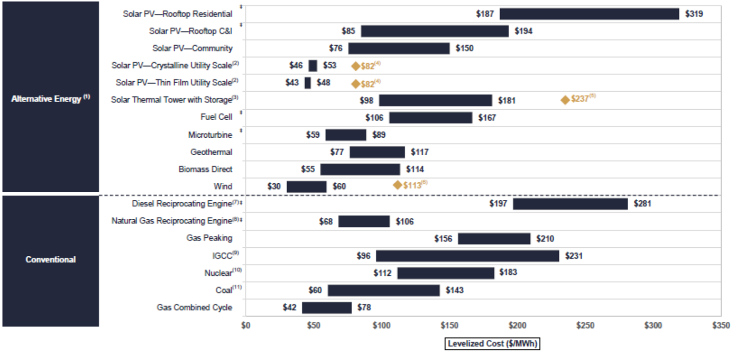

return

# Levelized Cost of Electricity

LAZARD'S LEVELIZED COST OF ENERGY ANALYSIS—VERSION 11.0

## Unsubsidized Levelized Cost of Energy Comparison

**Certain Alternative Energy generation technologies are cost-competitive with conventional generation technologies under some scenarios; such observation does not take into account potential social and environmental externalities (e.g., social costs of distributed generation, environmental consequences of certain conventional generation technologies, etc.), reliability or intermittency-related considerations (e.g., transmission and back-up generation costs associated with certain Alternative Energy technologies)**



# The optimal solution with variability only

## Dynamics of the carbon value, the shadow value of solar panels and solar capacity

- Carbon value $\lambda$ before the carbon budget is exhausted:

$$\lambda(t) = \lambda(0)e^{\rho t}$$

- Solar capacity over the whole horizon:

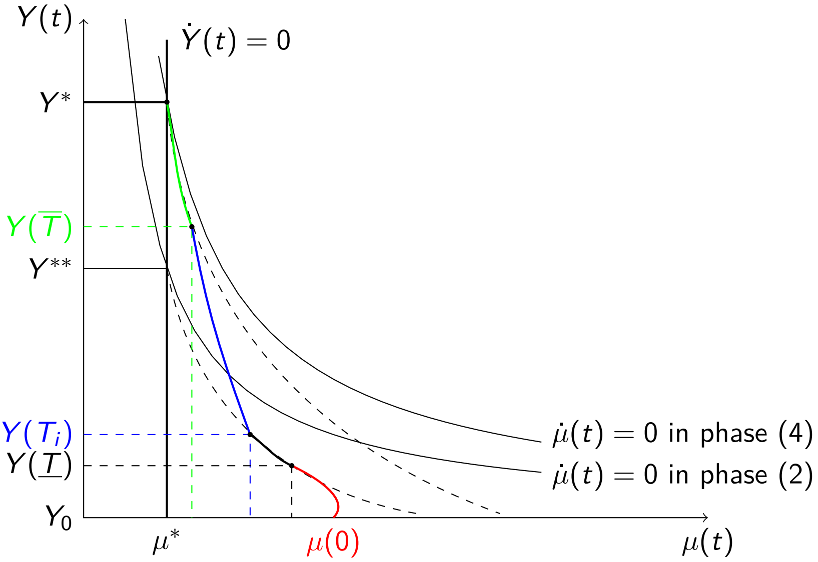
$$\dot{Y}(t) = \frac{1}{c_2}(\mu(t) - c_1)$$

- Shadow value of solar capacity in each phase:

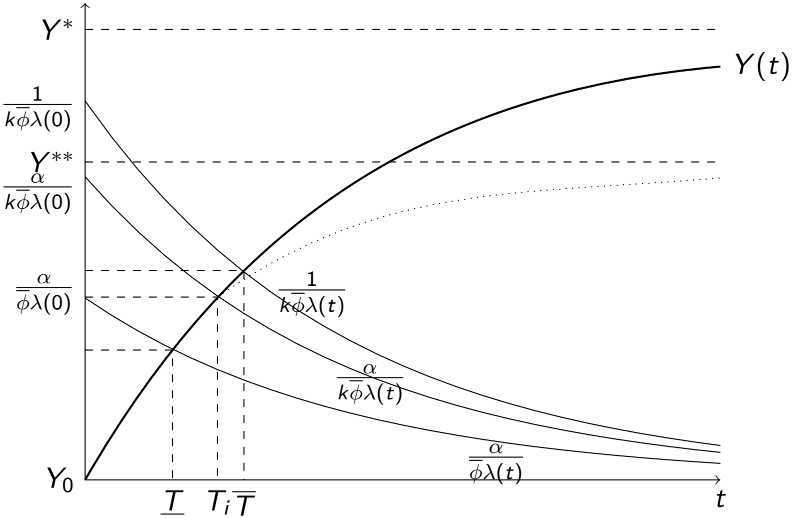
$$\begin{aligned}
&\text{Phase (1)} \qquad \dot{\mu}(t) = \rho\mu(t) - \overline{\phi}\lambda(t) \\
&\text{Phase (2)} \qquad \dot{\mu}(t) = \rho\mu(t) - \frac{\alpha}{Y(t)} \\
&\text{Phase (3)} \qquad \dot{\mu}(t) = \rho\mu(t) - k\overline{\phi}\lambda(t) \\
&\text{Phase (4)} \qquad \dot{\mu}(t) = \rho\mu(t) - \frac{1}{Y(t)}
\end{aligned}$$

equations

# The optimal solution with variability only
## Phase diagram



# The optimal solution with variability only
## Solar capacity and carbon value before the ceiling



# Fossil fuel use, storage and total electricity consumption in each phase

Phase (1)

$$x_d(t) = \frac{\alpha}{\lambda(t)} - \overline{\phi}Y(t) \qquad x_n(t) = \frac{1-\alpha}{\lambda(t)} \qquad a(t) = 0$$

$$e_d(t) = \frac{\alpha}{\lambda(t)} \qquad e_n(t) = \frac{1-\alpha}{\lambda(t)}$$

$$p_d(t) = \lambda(t) \qquad p_n(t) = \lambda(t)$$

Phase (2)

$$x_d(t) = 0 \qquad x_n(t) = \frac{1-\alpha}{\lambda(t)} \qquad a(t) = 0$$

$$e_d(t) = \overline{\phi}Y(t) \qquad e_n(t) = \frac{1-\alpha}{\lambda(t)}$$

$$p_d(t) = \frac{\alpha}{\overline{\phi}Y(t)} \qquad p_n(t) = \lambda(t)$$

Phase (3)

$$x_d(t) = 0 \qquad x_n(t) = \frac{1}{\lambda(t)} - k\overline{\phi}Y(t) \qquad a(t) = 1 - \frac{\alpha}{k\lambda(t)\overline{\phi}Y(t)}$$

$$e_d(t) = \frac{\alpha}{k\lambda(t)} \qquad e_n(t) = \frac{1-\alpha}{\lambda(t)}$$

$$e_d(t) = k\lambda(t) \qquad p_n(t) = \lambda(t)$$

Phase (4)

$$x_d(t) = 0 \qquad x_n(t) = 0 \qquad a^* = 1 - \alpha$$

$$e_d(t) = \alpha\overline{\phi}Y(t) \qquad e_n(t) = (1-\alpha)k\overline{\phi}Y(t)$$

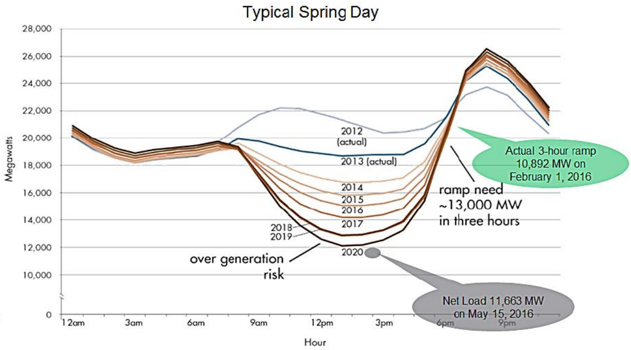
$$p_d(t) = \frac{1}{\overline{\phi}Y(t)} \qquad p_n(t) = \frac{1}{k\overline{\phi}Y(t)}$$

return

# The Duck Chart (CAISO)

When sun is shining at off-peak time.

Figure 2: The duck curve shows steep ramping needs and overgeneration risk




return