Distributed Storage for Intermittent Energy Sources: Control Design and Performance Limits

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Joint work with:
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The challenge of renewables

- Intermittent
- Intrinsically distributed

How to manage?

Strategy	Requirement
Spatial averaging	Transmission
Time averaging	Storage
Over-provisioning	Generation
Demand response	Signaling, incentives

The paper

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- Intermittent
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How to manage?

This talk: Spatial averaging, Time averaging

Strategy	Requirement
Spatial averaging	Transmission
Time averaging	Storage
Over-provisioning	Generation
Demand response	Signaling, incentives

Questions?

- Optimal control of grid with transmission and storage?
- Infrastructure improvement:
  - New transmission line? Upgrade in existing line?
  - New storage facility?
  - New generation?

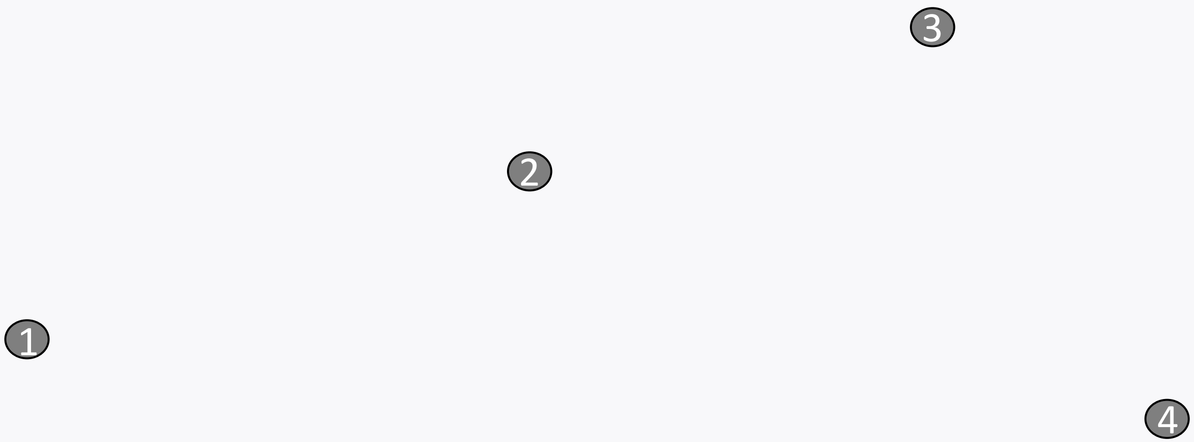
  Which will help more?

  How to optimally allocate budget?

Our contribution

- Control design for discrete time model
- Analytical insights quantifying benefits of storage, transmission and overprovisioning

Model



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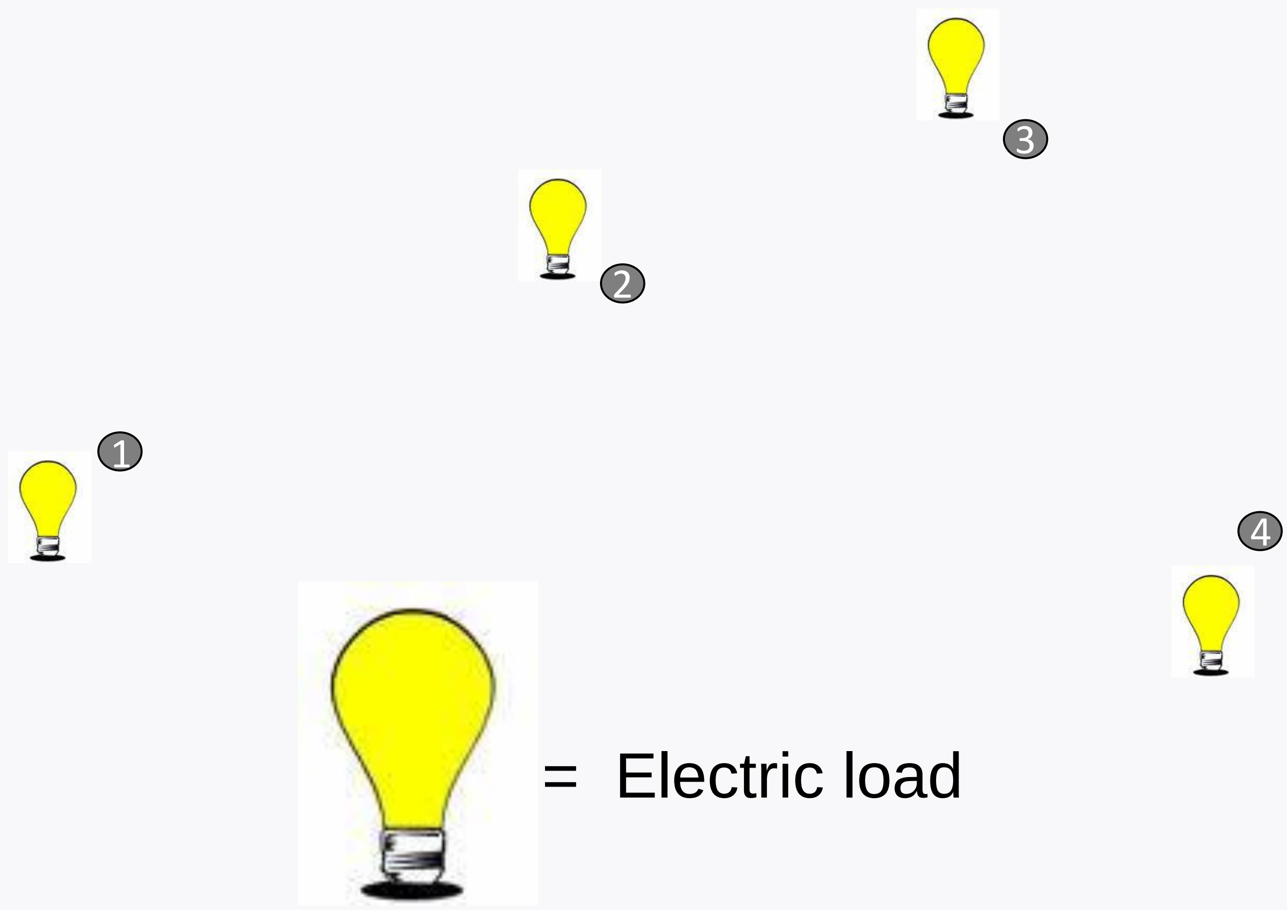

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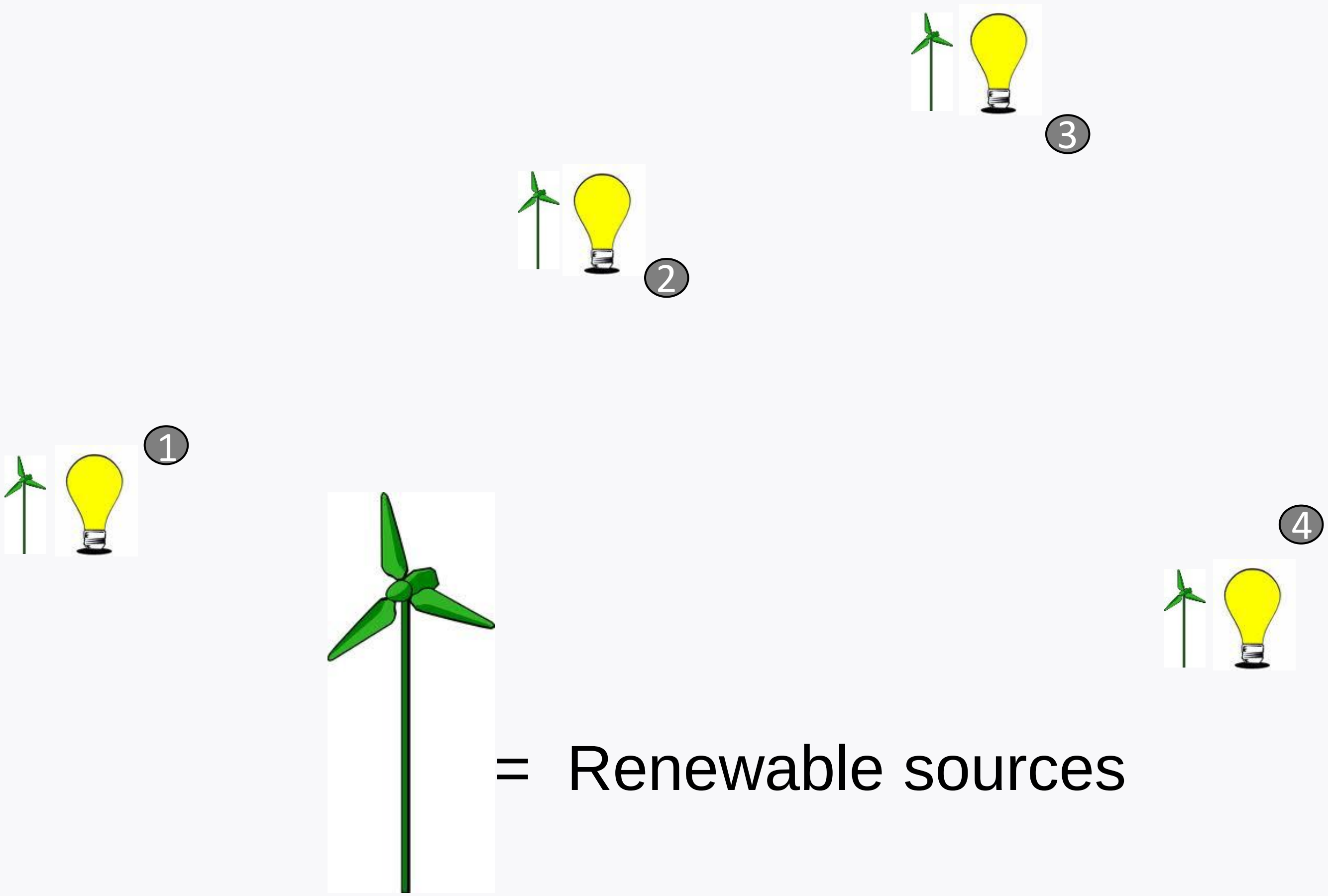

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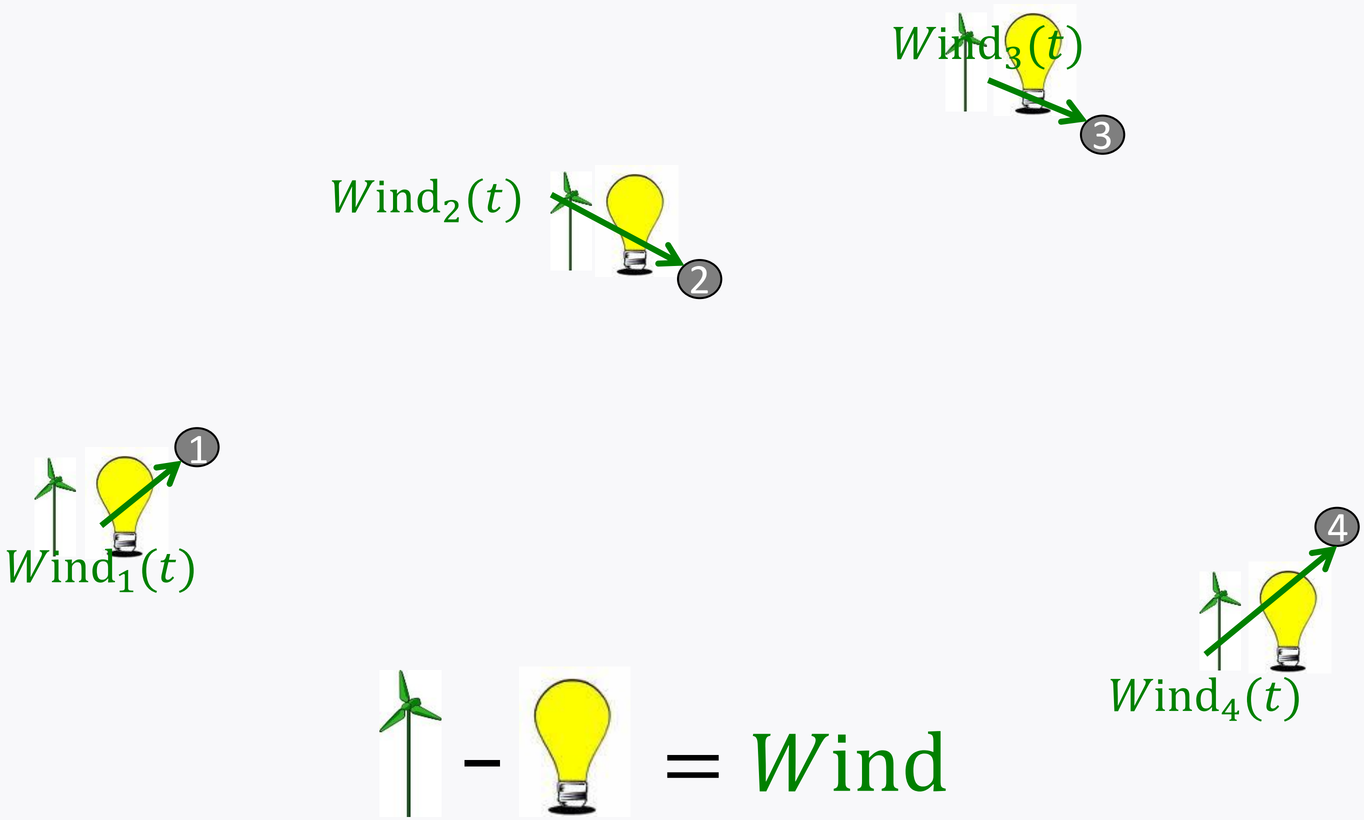
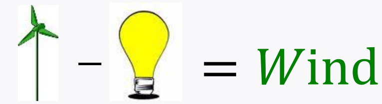
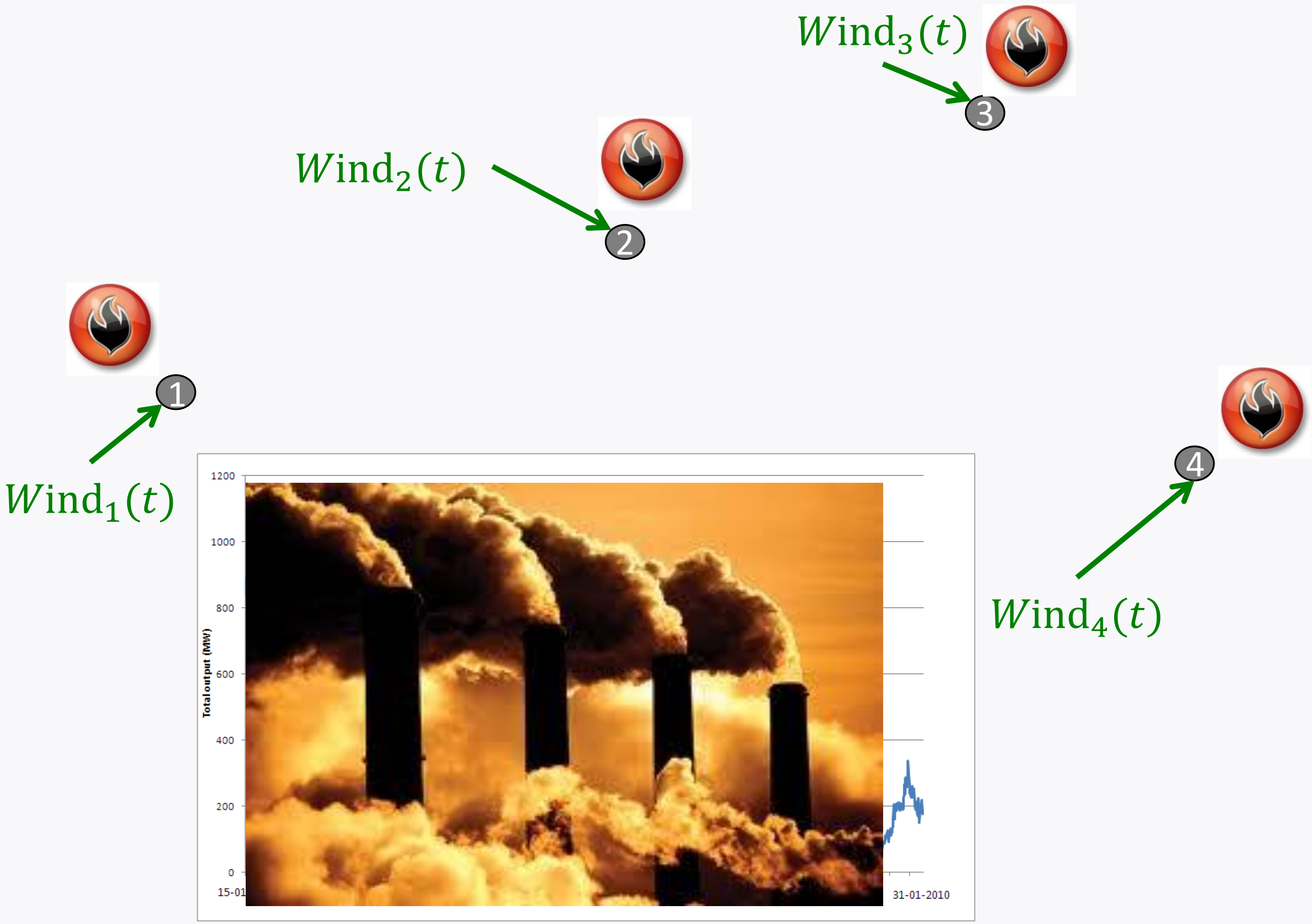
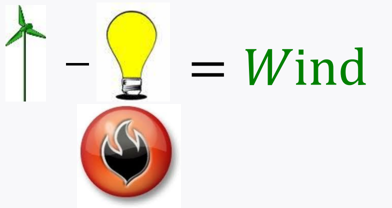


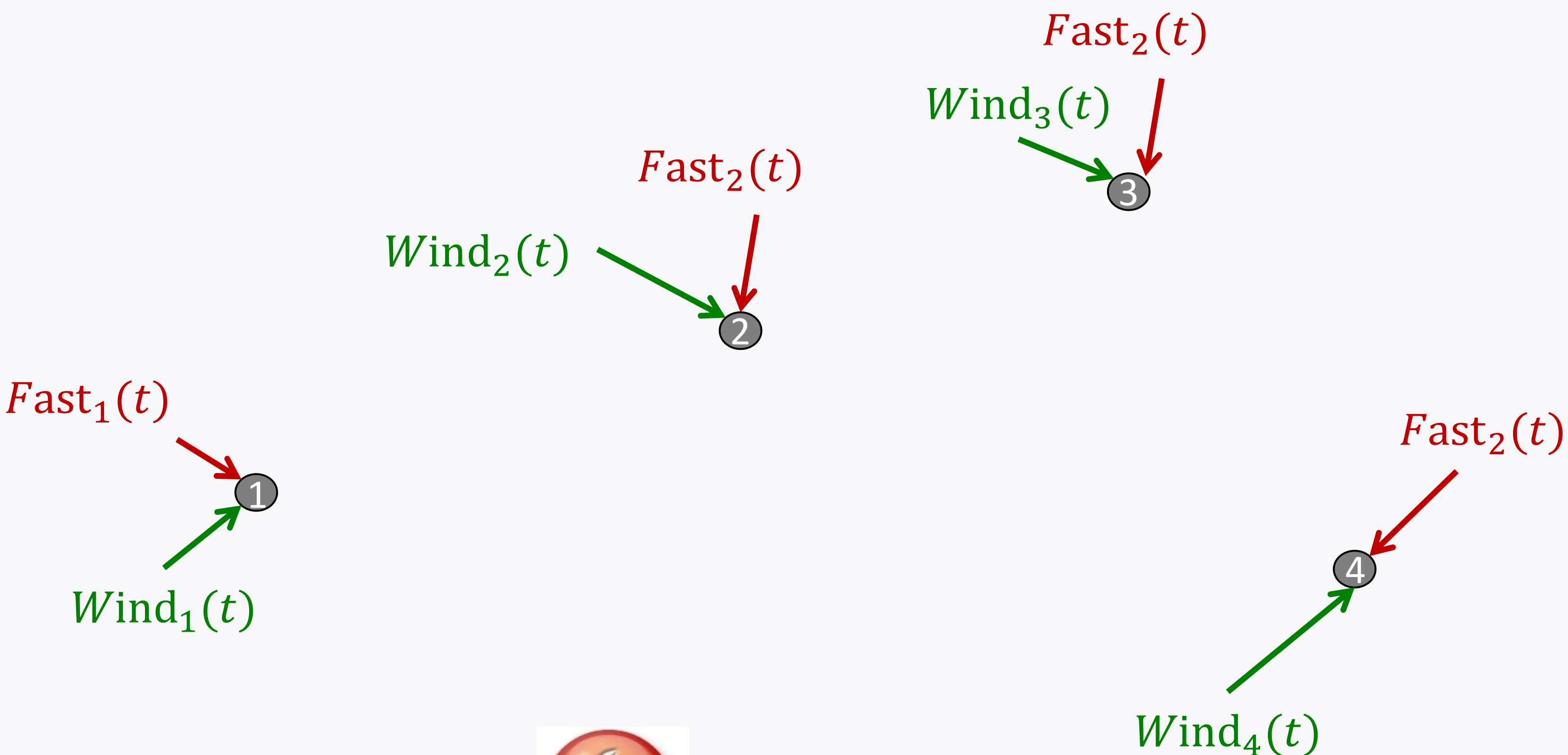

$-$ $= Wind$

Model


$Wind_3(t)$
3
$Wind_2(t)$
2
1
$Wind_1(t)$
4
$Wind_4(t)$
1200
1000
800
600
400
200
0
Total output (MW)
15-01
31-01-2010

Model

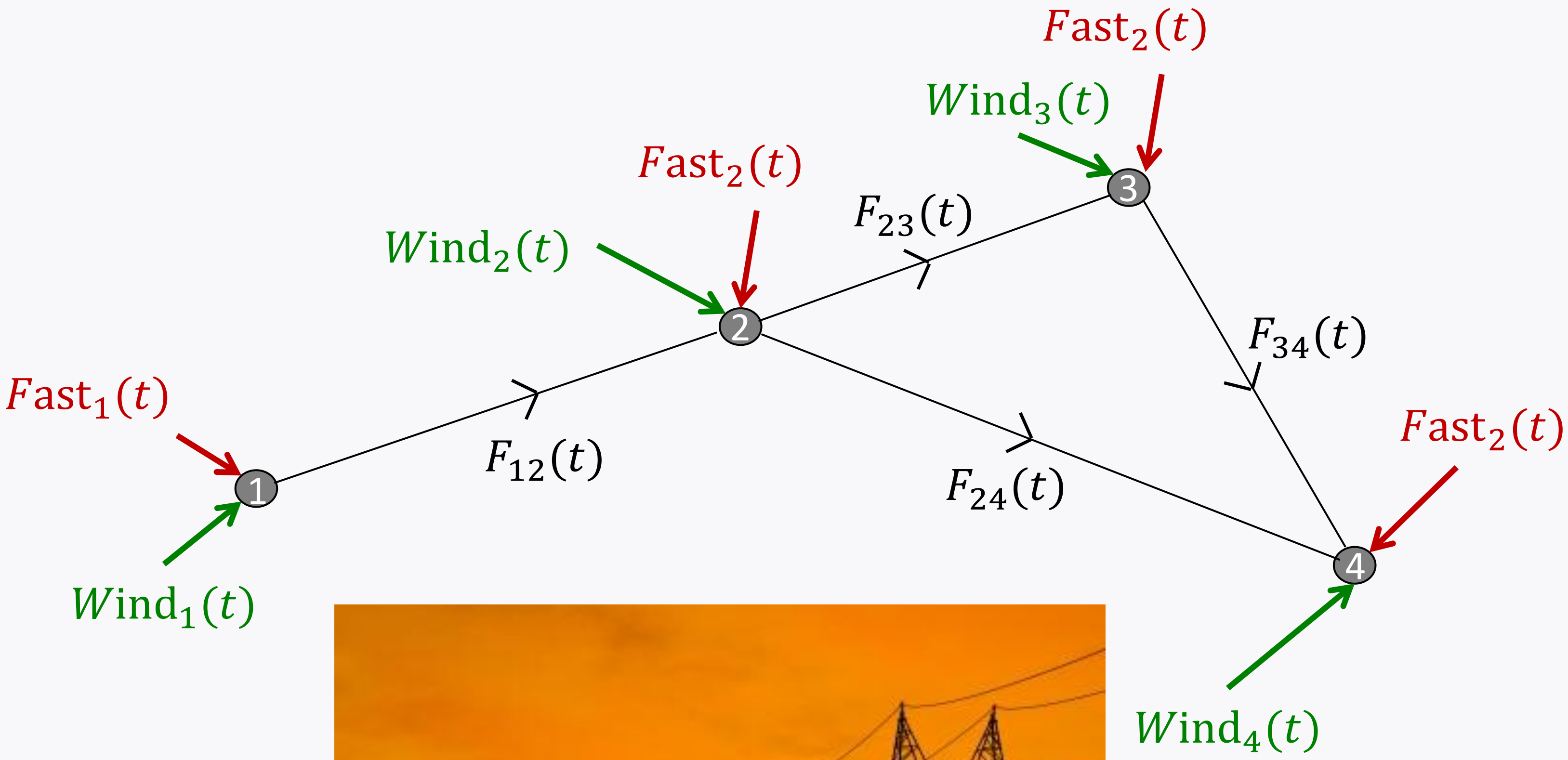

−
= $Wind$


$Fast_2(t)$
$Wind_3(t)$
3
$Fast_2(t)$
$Wind_2(t)$
2
$Fast_1(t)$
1
$Wind_1(t)$
$Fast_2(t)$
4
$Wind_4(t)$

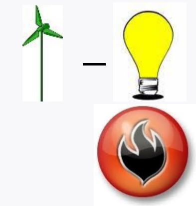
= $Fast$

Model

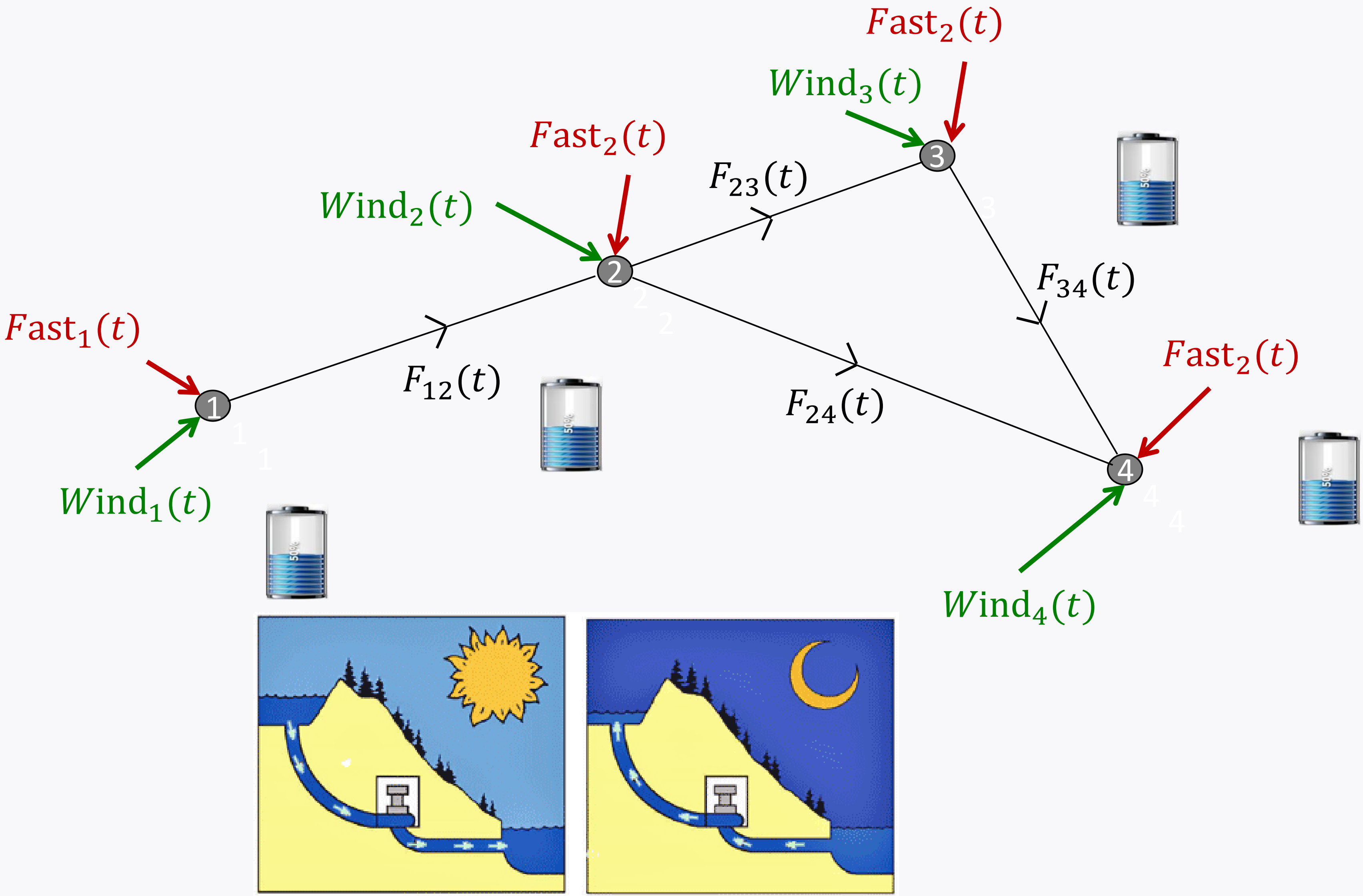

− = $Wind$
= $Fast$


$Fast_2(t)$
$Wind_3(t)$
$Fast_2(t)$
$F_{23}(t)$
$Wind_2(t)$
3
2
$F_{34}(t)$
$Fast_1(t)$
$F_{12}(t)$
$F_{24}(t)$
$Fast_2(t)$
1
4
$Wind_1(t)$
$Wind_4(t)$

Model

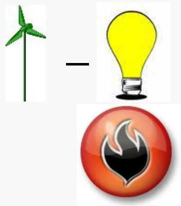


= $Wind$
= $Fast$



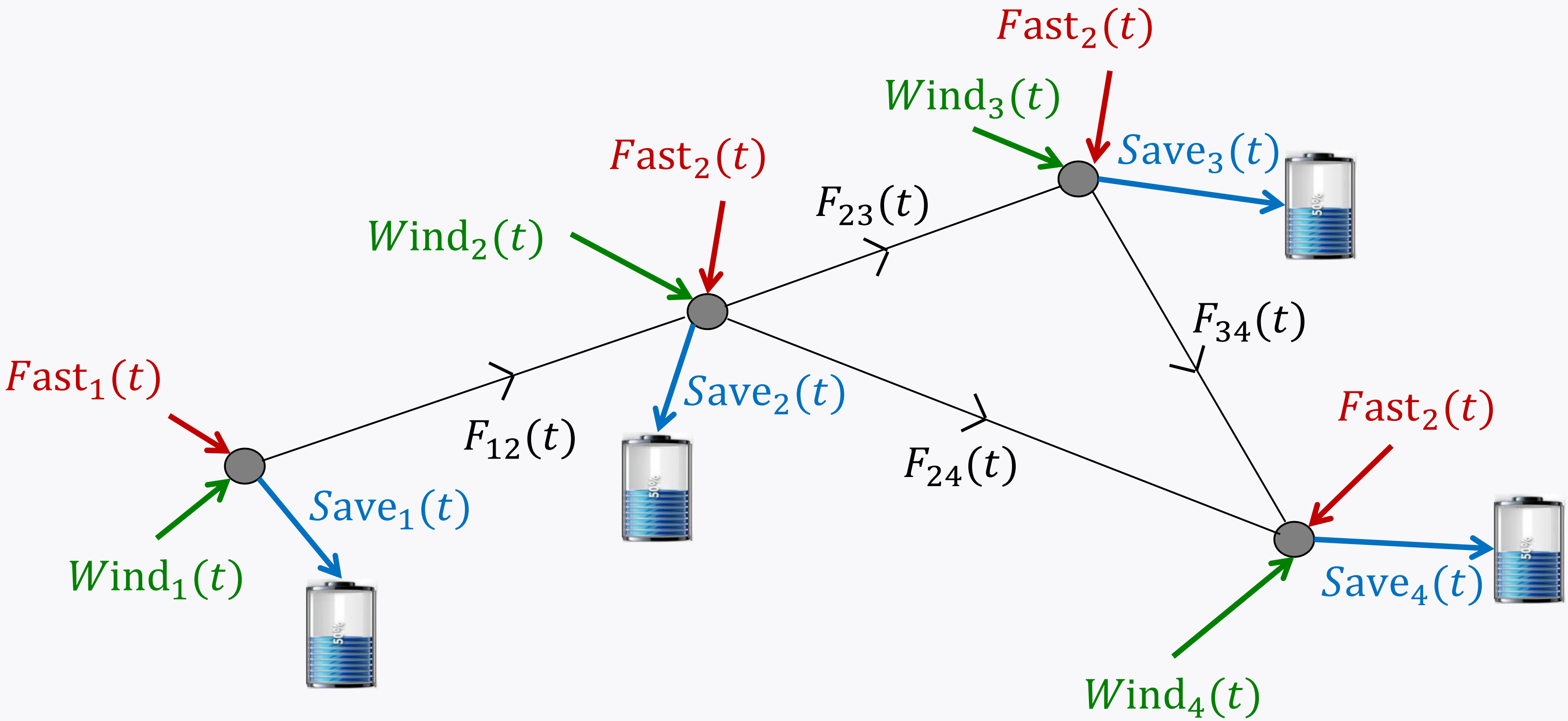
$Fast_1(t)$
$Wind_1(t)$
$F_{12}(t)$
$Wind_2(t)$
$Fast_2(t)$
$F_{23}(t)$
$Wind_3(t)$
$Fast_2(t)$
$F_{24}(t)$
$F_{34}(t)$
$Fast_2(t)$
$Wind_4(t)$
1
2
3
4
50%

Model



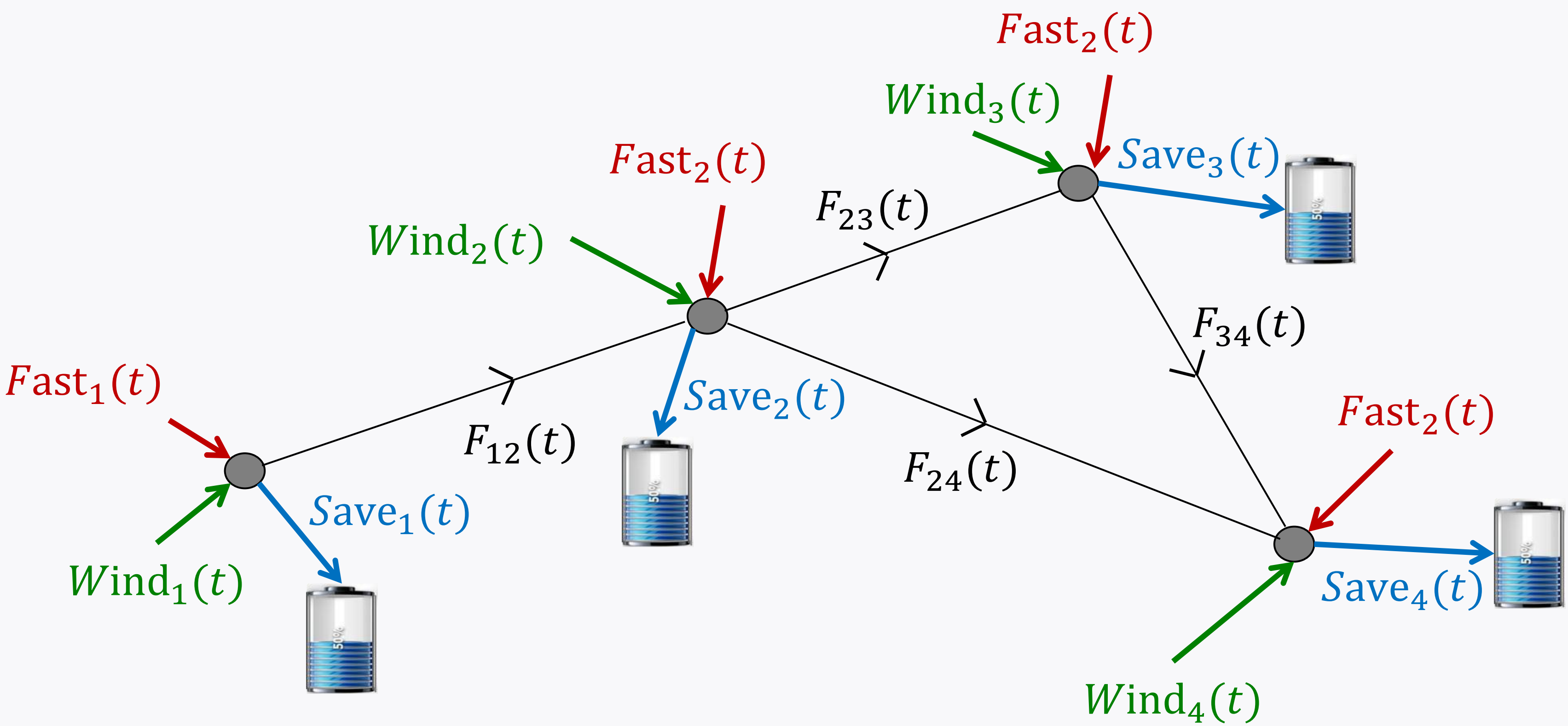
$- \quad = \mathit{Wind}$

$= \mathit{Fast}$



Energy pushed into  $= \mathit{Save}$

Model



Control inputs:

- $Fast_i(t)$
- $Save_i(t)$

Dependent variables:

- Flows $F_{ij}(t)$
- Storage buffers $B_i(t)$

Constraints

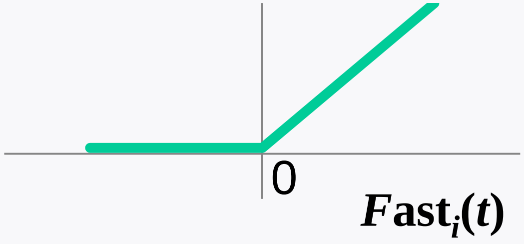
- Storage capacity constraints
  Hard constraint

- Transmission constraints
  Soft constraint

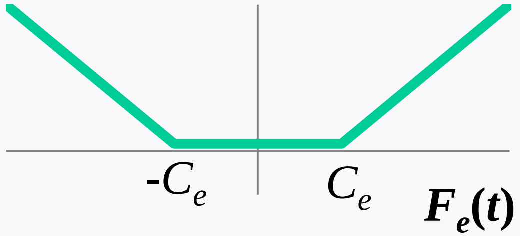
Cost function

- ε_{Fast} = Cost of fast generation

  (free disposal of energy)



- ε_F = Cost of violating transmission constraints



- Performance criterion: $\boldsymbol{\varepsilon = \varepsilon_{Fast} + \varepsilon_F}$

What's the issue?

- Centralized control problem 
- $F(t)$ is linear function of controls 
- Storage constraints cause thresholding 
- Non-quadratic cost function 

Idea: Use surrogate cost function

$$\mathrm{Var}(Fast) + \lambda\,\mathrm{Var}(F) + \hat{\lambda}\,\mathrm{Var}(B)$$

(drop storage constraints for now)

The surrogate problem

- ‘State’ consisting of buffer sizes
- ‘Noise’ $W\mathrm{ind}(t)$
- State and noise fully observed
- Linear state evolution
- Quadratic cost
- Assume $W\mathrm{ind}(t)$ is Gaussian

We have an LQG problem!

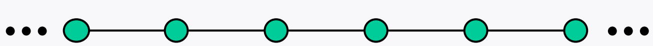
- Can be solved numerically yielding control scheme
- Can be mapped back to original problem

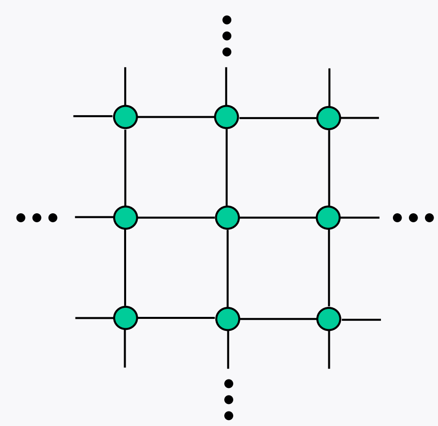
The surrogate LQG problem

- Is the scheme any good?
- Any insights into roles of storage and transmission?

Specific networks

- Transmission network is almost a tree
- What happens on an infinite line?
- What about a two-dimensional grid?

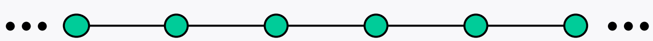


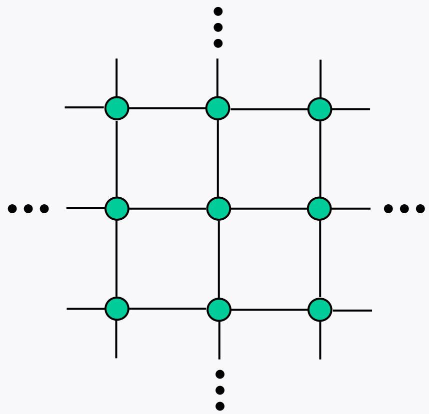


1-D and 2-D grids

Assume:

- Storage S at each node
- Capacity C on each line
- $W\mathrm{ind}_i(t) \sim \mathrm{N}(0, \sigma^2)$ iid





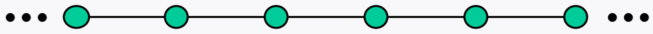
1-D and 2-D grids

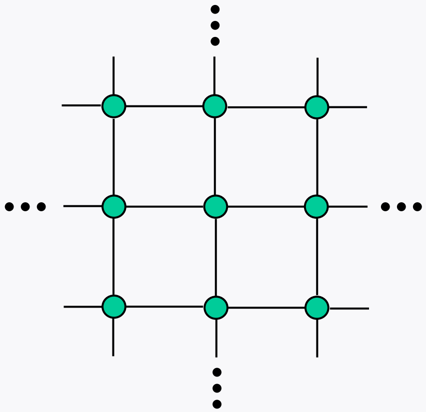
S = Storage
C = Transmission
$\sigma^2 = \mathrm{Var}(W\mathrm{ind})$

We find, for original problem:

- Analytical expressions for cost of LQG-based schemes
- Fundamental limits

⇒ LQG is near optimal





Results $\varepsilon = \varepsilon_{Fast} + \varepsilon_F$

S = Storage
C = Transmission
$\sigma^2 = \mathrm{Var}(Wind)$

	Only S	Only C	$C = S$
1-D grid		$\frac{\sigma^2}{C}$	$\sigma \exp\left(-\frac{C}{\sigma}\right)$
2-D grid	$\frac{\sigma^2}{S}$	$\sigma \exp\left(-\frac{C}{\sigma}\right)$	$\sigma \exp\left(-\frac{C^2}{\sigma^2}\right)$

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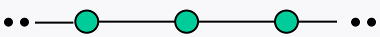

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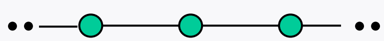

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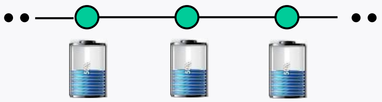

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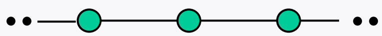

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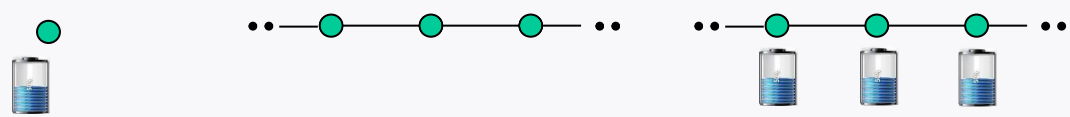

C and S together works best!

Results $\varepsilon = \varepsilon_{Fast} + \varepsilon_F$

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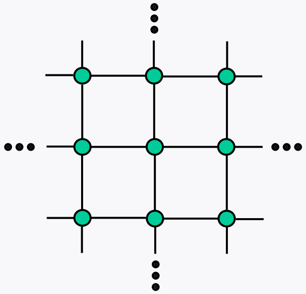

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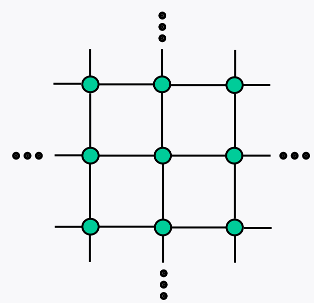

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Averaging over 2-D much more effective than 1-D

Results $\varepsilon = \varepsilon_{Fast} + \varepsilon_F$

S = Storage
C = Transmission
$\sigma^2 = \mathrm{Var}(W\mathrm{ind})$

	Only S	Only C	$C = S$
1-D grid	$\frac{\sigma^2}{S}$	$\frac{\sigma^2}{C}$	$\sigma \exp\left(-\frac{C}{\sigma}\right)$
2-D grid	$\frac{\sigma^2}{S}$	$\sigma \exp\left(-\frac{C}{\sigma}\right)$	$\sigma \exp\left(-\frac{C^2}{\sigma^2}\right)$

S seems to provide extra dimension for averaging!

Intuition: Time is like extra spatial dimension

Results $\varepsilon = \varepsilon_{Fast} + \varepsilon_{F}$

S = Storage
C = Transmission
$\sigma^2 = \mathrm{Var}(Wind)$

	Only S	Only C	$C = S$
1-D grid	$\frac{\sigma^2}{S}$	$\frac{\sigma^2}{C}$	$\sigma \exp\left(-\frac{C}{\sigma}\right)$
2-D grid	$\frac{\sigma^2}{S}$	$\sigma \exp\left(-\frac{C}{\sigma}\right)$	??

Results $\varepsilon = \varepsilon_{Fast} + \varepsilon_F$

S = Storage
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$\sigma^2 = \mathrm{Var}(W\mathrm{ind})$

	Only S	Only C	$C = S$
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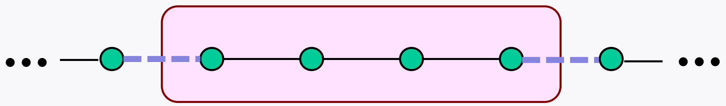
2-D grid	$\frac{\sigma^2}{S}$	$\sigma \exp\left(-\frac{C}{\sigma}\right)$	$\sigma \exp\left(-\frac{C^2}{\sigma^2}\right)$

Spatial averaging is much easier in 2-D

1-D



Segment of length l

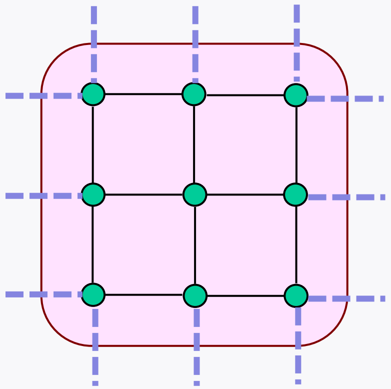
$$\text{Std. dev} = \sigma\sqrt{l}$$

$$\text{Cut size} = 2C$$

$\Rightarrow$ Can only average over

$$l \lesssim \frac{C^2}{\sigma^2}$$

2-D



Square of side l

$$\text{Std. dev} = \sigma l$$

$$\text{Cut size} = 4Cl$$

Both scale together!

$\Rightarrow$ Can average over large l.

Conclusions and future work

- Gaussian assumption optimistic
- But key insights should remain valid:
  - 2-D averaging much better than 1-D
  - S facilitates averaging over extra dimension
- In the paper: A little overprovisioning can go a long way

Thank you!