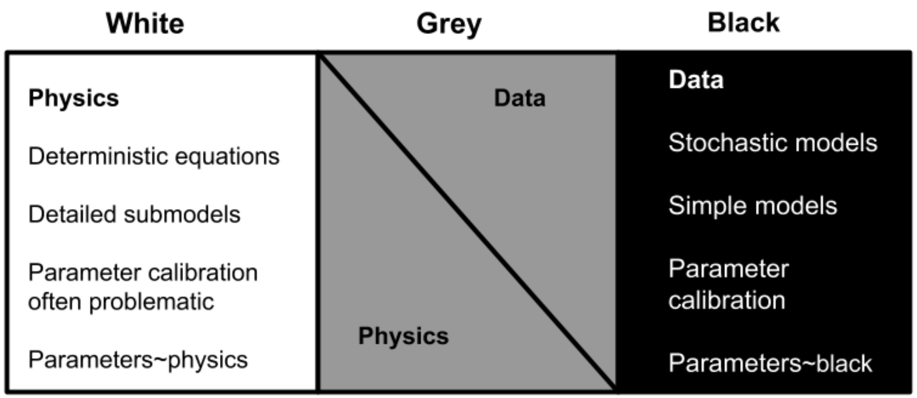
Innovation Fund Denmark

DTU

Fusion of Data and Physics-Based Modeling; State-of-the-Art and Applications



Henrik Madsen

Technical University of Denmark

http://www.smart-cities-centre.org

https://www.flexibleenergydenmark.dk

http://www.henrikmadsen.org

CITIES Centre for IT Intelligent Energy Systems

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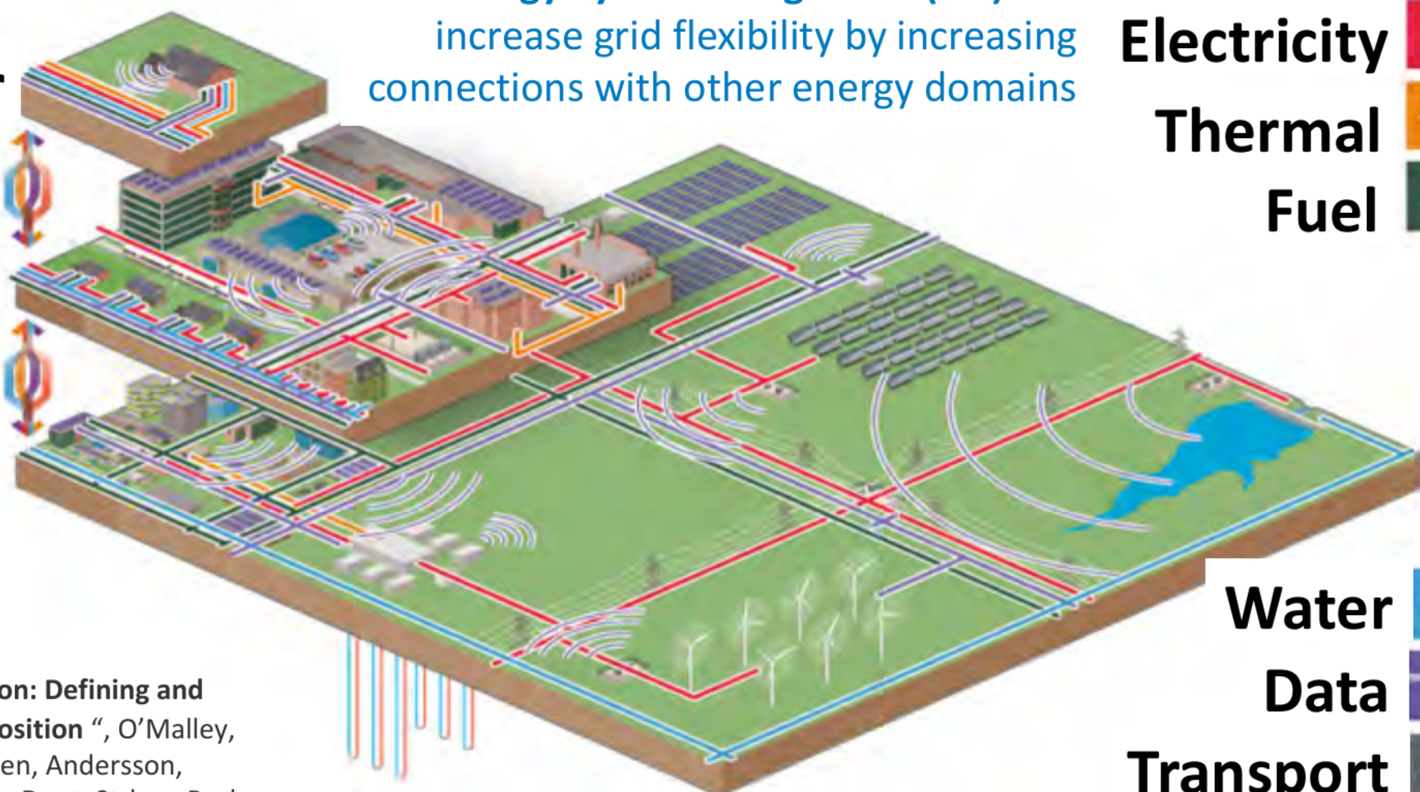
Energy Systems Integration

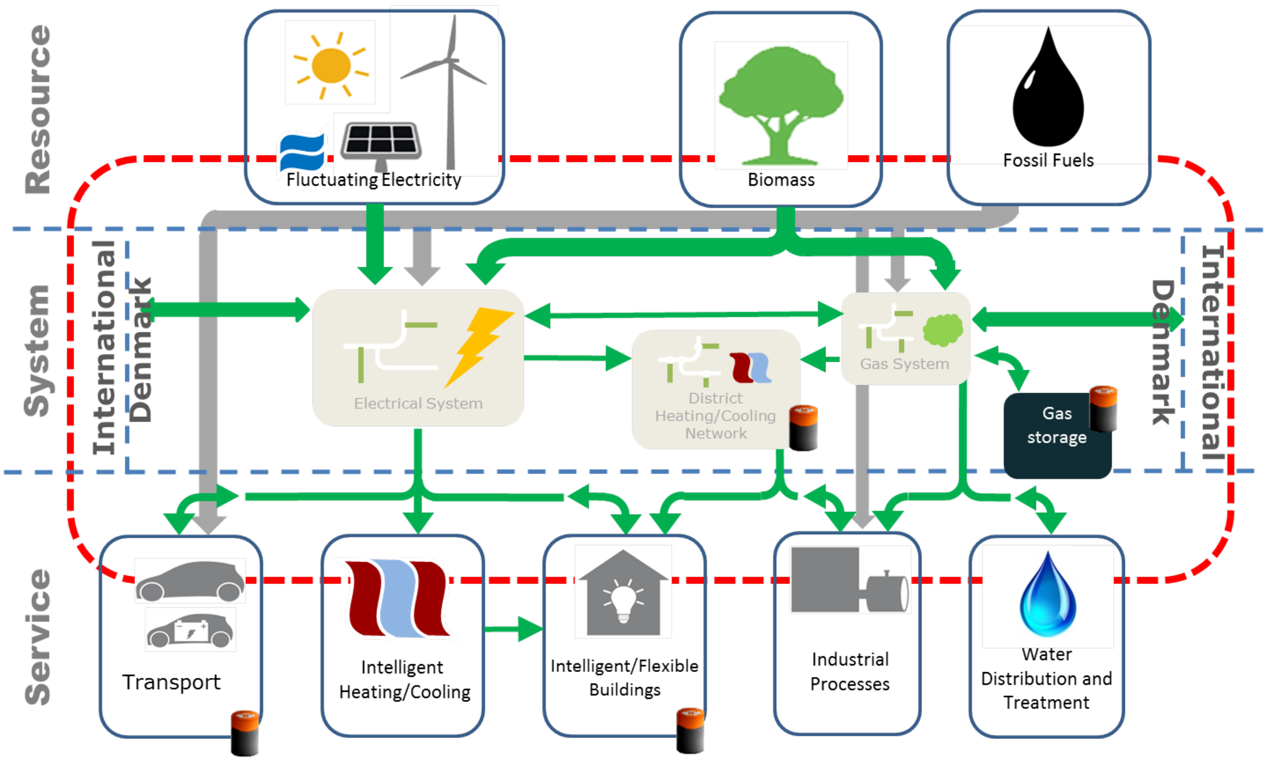
Energy System Integration (ESI) can increase grid flexibility by increasing connections with other energy domains



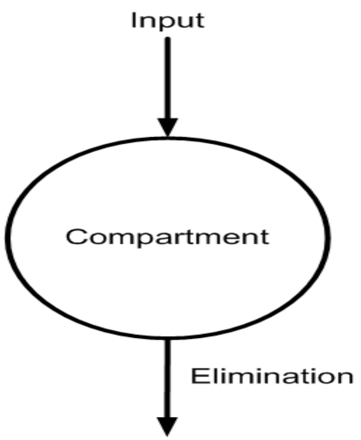
"Energy Systems Integration: Defining and Describing the Value Proposition ", O'Malley, Kroposki, Hannegan, Madsen, Andersson, D'haeseleer, McGranaghan, Dent, Strbac, Baskaran, Rinker., NREL/TP-5D00-66616. June 2016

Energy System Models for Real Time Applications and Data Assimilation

- **Grey-box models are simplified models for the individual components facilitating system integration and use of sensor data**

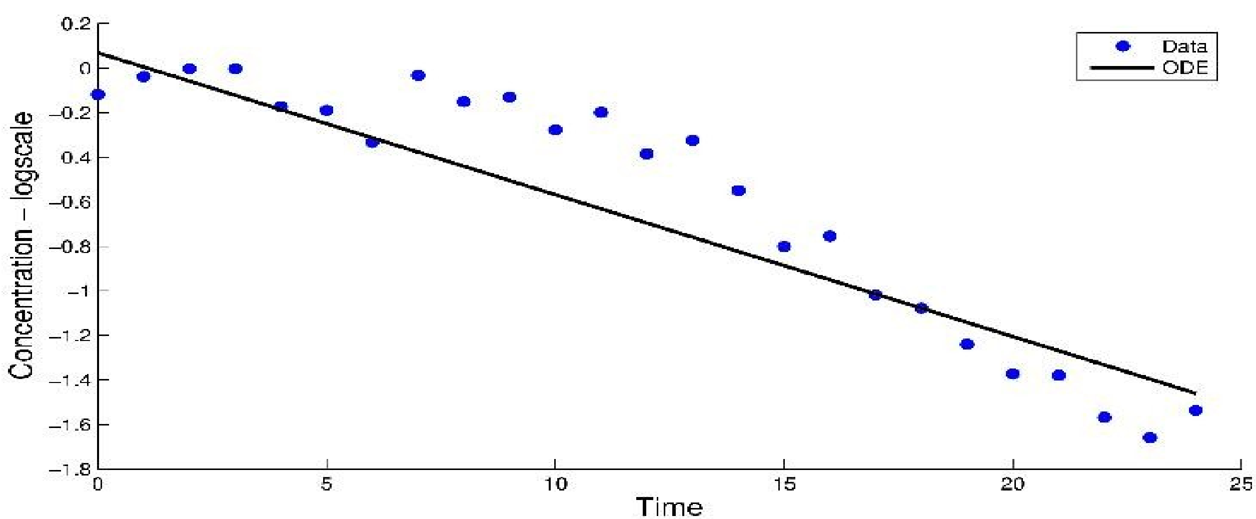


Traditional Dynamical Model

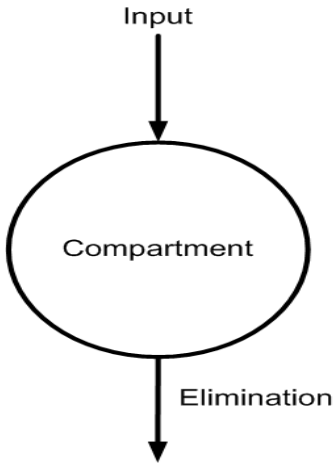


- Ordinary Differential Equation:

$$
\begin{aligned}
dA &= -KAdt \\
Y &= A + \epsilon
\end{aligned}
$$

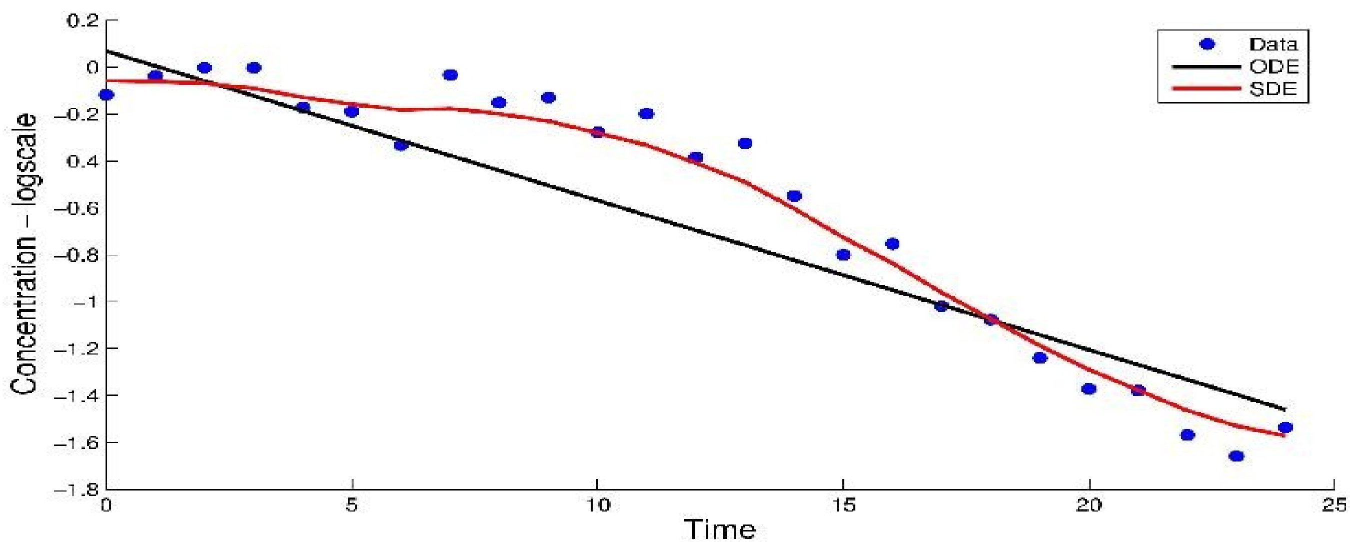


Stochastic Dynamical Model



- Stochastic Differential Equation:

$$
\begin{aligned}
dA &= -KA\,dt + \sigma\,dw \\
Y &= A + e
\end{aligned}
$$



Grey box or HMM model on state space form

Drift term

Diffusion term

$$dX_t = f(X_t, u_t, t, \theta)dt + \sigma(X_t, u_t, t, \theta)d\omega_t \qquad \text{System equation}$$

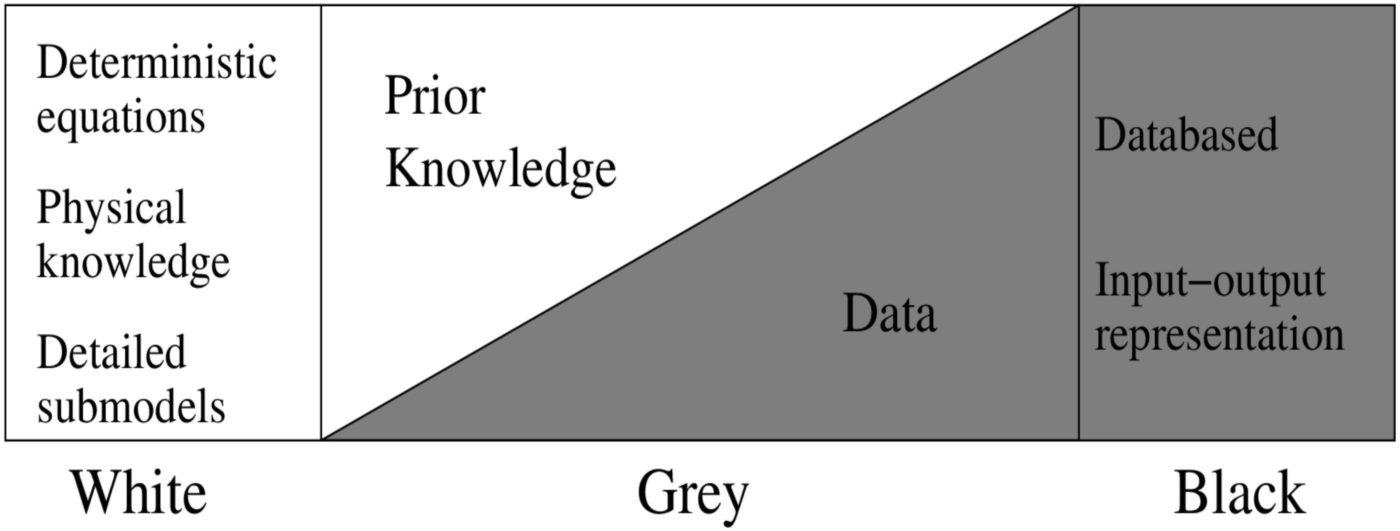
$$Y_k = h(X_k, u_k, t_k, \theta) + e_k, \qquad \text{Observation equation}$$

Observation noise

Notation:

X_t:	State variables
u_t:	Input variables
θ:	Parameters
Y_k:	Output variables
t:	Time
ω_t:	Standard Wiener process
e_k:	White noise process with $N(0, S)$

Grey-box modeling concept



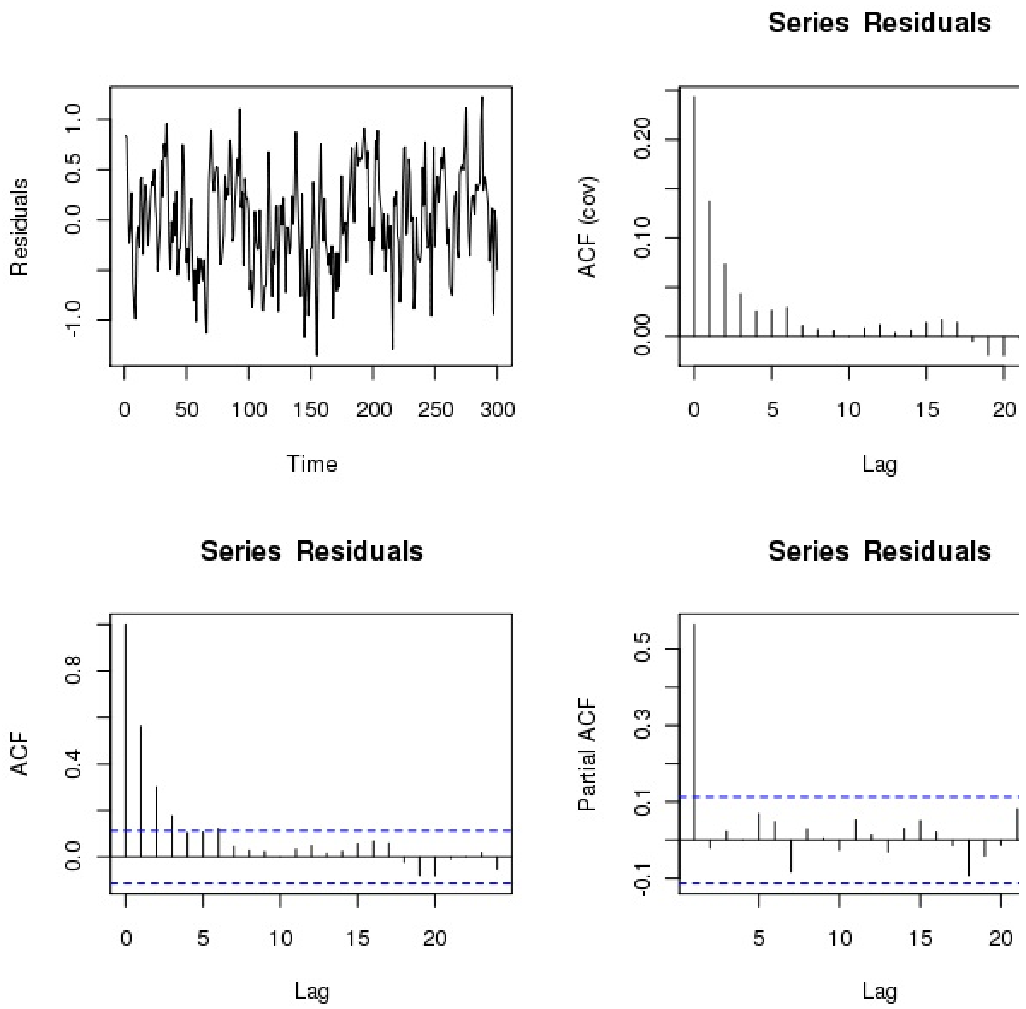
- Combines prior physical knowledge with information in data
- Equations and parameters are physically interpretable

Grey-Box models are well suited for ...

- One-step forecasts
- Software state estimation (software sensors)
- K-step forecasts
- Simulations
- Control
- …

- **Provides a framework for pinpointing model deficiencies – like:**
  - Time-tracking of unexplained variations in e.g. parameters
  - Missing (differential) equations
  - Missing functional relations
  - Lack of proper description of the uncertainty

Identification of the needed number of states / differential equations (example)



The software ...

- CTSM-R – *Continuous Time Stochastic Modelling in R*
- Download from http://ctsm.info
- **User's** and **Math Guides** are available
- For more information:

  Email to

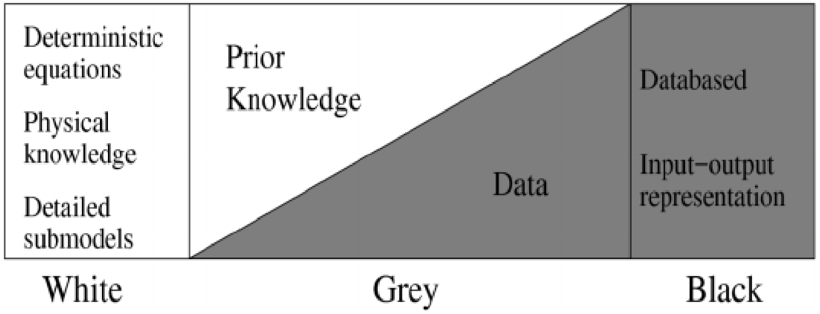
  info@ctsm.info

Example on

Blade manufacturing (molding) …

Monitoring and Modelling Framework

- Sensors
  - It would require a lot of sensors to get the full picture
- Computational Fluid Dynamics
  - Solving multidimensional PDEs in real-time is computationally heavy
- Greybox Models
  - We combine knowledge from physical models with sensor data to further develop our models and to explain discrepancies



Simulation of Flow-Front Progression

- We combine Darcy's law with the equation for conservation of mass

$$q = -\frac{\kappa H}{\mu} \nabla p$$

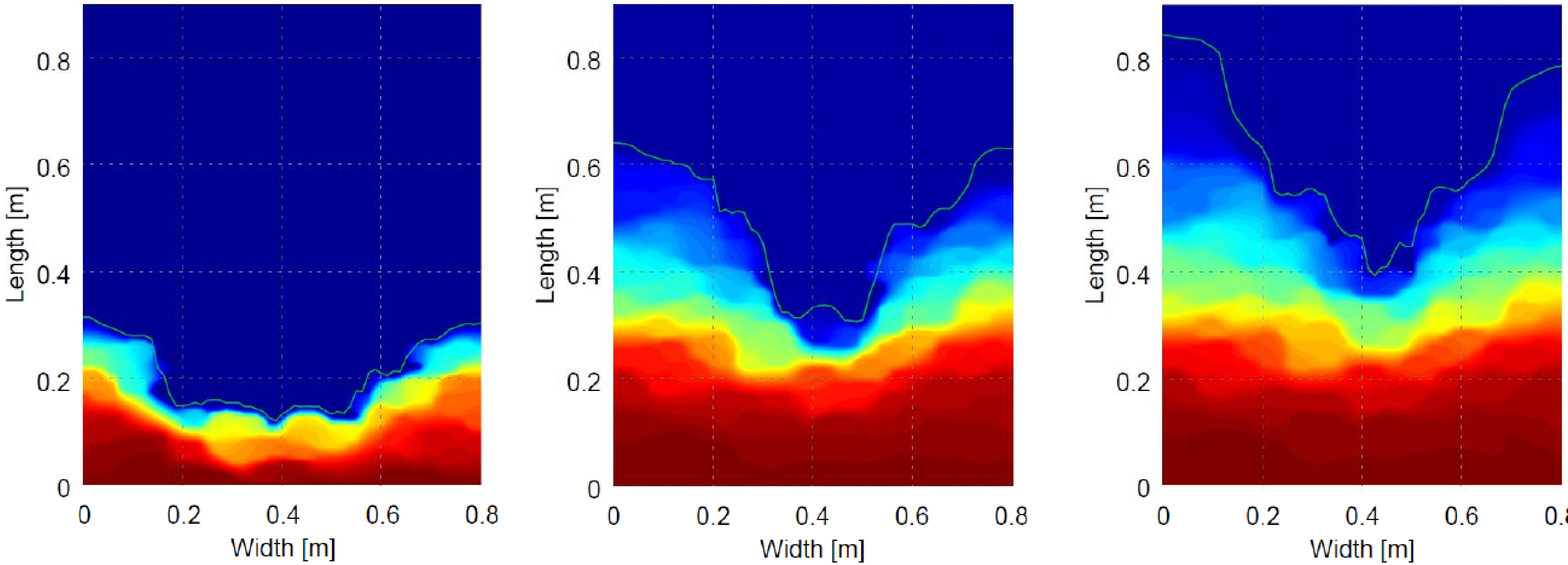
$$\dot{h} + \nabla \cdot q = 0$$

$$\dot{h} = \frac{dh}{dp}\dot{p} = \nabla \cdot (\frac{\kappa H}{\mu} \nabla p)$$

$$q = q(x, y, t), \; \nabla = (\partial_x, \partial_y)$$

$$h = min(H, \frac{p}{\rho g})$$

Simulation of Flow-Front Progression



Example on

Prob. Wind Power Forecasting

Prob. Wind Power Forecasting using SDEs

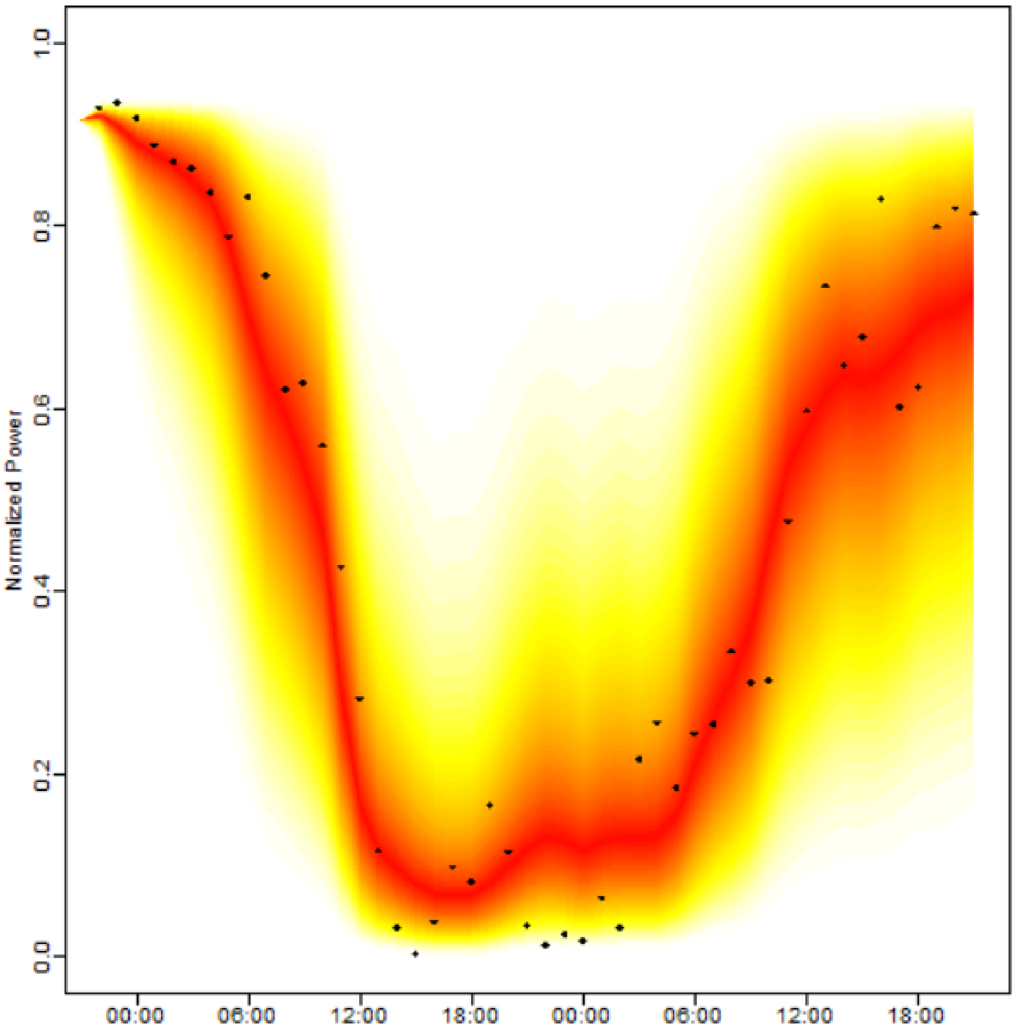
Wind dynamics given by:

$$
\begin{aligned}
dX_t &= \left(\left(1 - e^{-X_t}\right)(\rho_x \dot{p}_t + R_t) + \theta_x(p_t \mu_x - X_t)\right) dt + \sigma_x X_t^{0.5} dW_{x,t} \\
dR_t &= -\theta_r R_t dt + \sigma_r dW_{r,t} \\
Y_{1,k} &= X_{t_k} + \epsilon_{1,k}
\end{aligned}
$$

Wind to power dynamics given by:

$$
\begin{aligned}
dQ_t &= (S_t - \theta_q Q_t)dt + \sigma_q dW_{q,t} \\
dS_t &= -\theta_s S_t dt + \sigma_s dW_{s,t} \\
Y_{2,k} &= (0.5 + 0.5\tanh(5(X_{t_k} - \gamma_1)))\,(0.5 - 0.5\tanh(\gamma_2(X_{t_k} - \gamma_3))) \\
&\quad \frac{\zeta_3}{1 + e^{-\zeta_1(X_{t_k} - \zeta_2 + Q_{t_k})}} + \epsilon_{2,k}
\end{aligned}
$$

Predictive density of production in percent out of rated power for the Klim wind farm:



Examples on advanced topics …

(Solar power forecasting)

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Institut for Matematik og Computer Science

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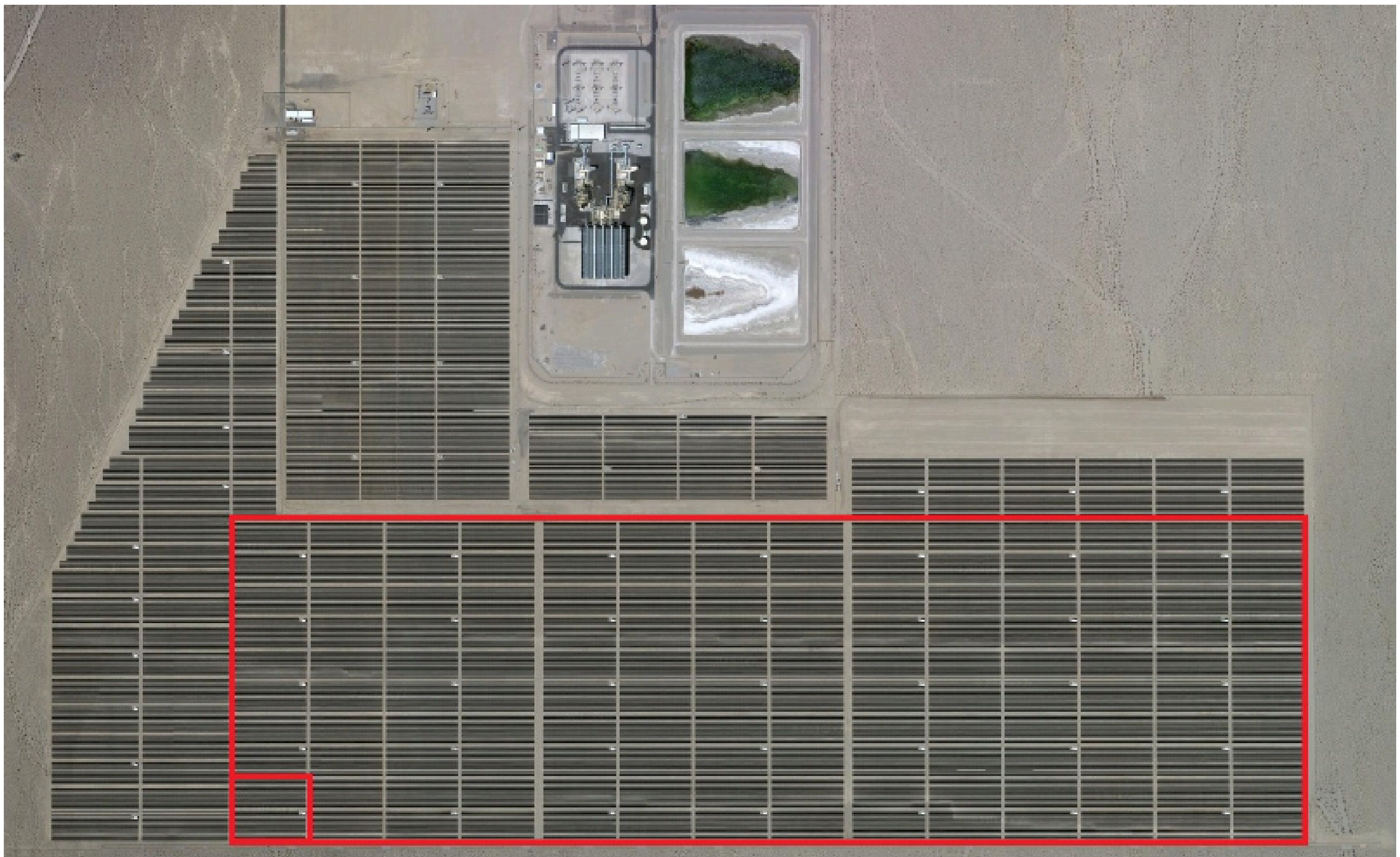
- A solar power plant with a nominal output of 151 MW.
- Measurements of 91 inverters every second for one year.
- We consider a cutout of 5 by 14 inverters for modeling.



Stochastic Partial Differential Equation

- Normalize the parameters with the spatial distance in appropriate way.
- Parameters become grid-invariant.
- Can be interpreted as a stochastic partial differential equation.

The dynamical model interpretation:

$$dU(x,t) \quad = \quad \bar{v}\theta\nabla U(x,t)dt + \sigma dW(x,t),$$

with the deterministic part $dU(x,t) = \bar{v}\theta\nabla U(x,t)dt$ being a uni-directional wave equation.

SPDE Model Performance

	Auto-Regressive	Model
$CRPS_5$	0.00262	**0.00131**
$CRPS_{20}$	0.00982	**0.00666**
$CRPS_{60}$	0.02886	**0.02455**
$CRPS_{120}$	0.04883	**0.04675**

Center Denmark

National Digitalization/AI Hub
for Smart Energy Systems and Integration of Wind/Solar Power


CENTER
DENMARK
Connect networks and data
for a green world
Danmarks
nationale Center
Fremme den grønne omstilling.
Samle og bygge bro, mellem
forskning, teknologi, natur og formidling,
på tværs af interesseorganisationer,
virksomheder, skoler og
universiteter.

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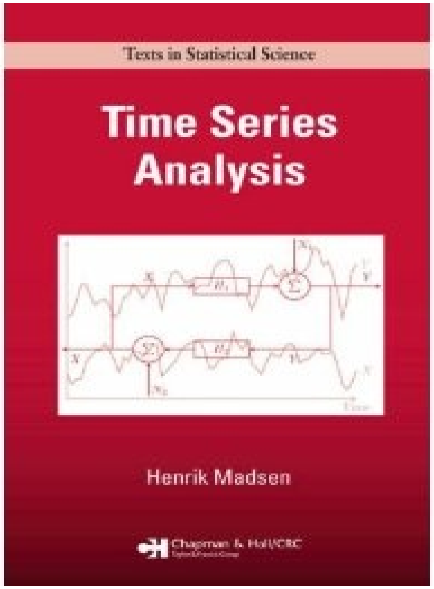
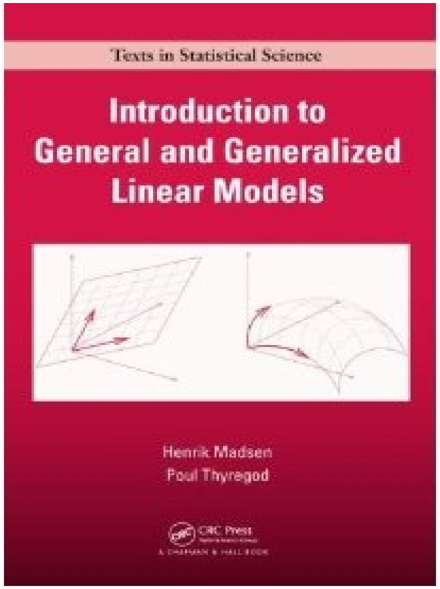
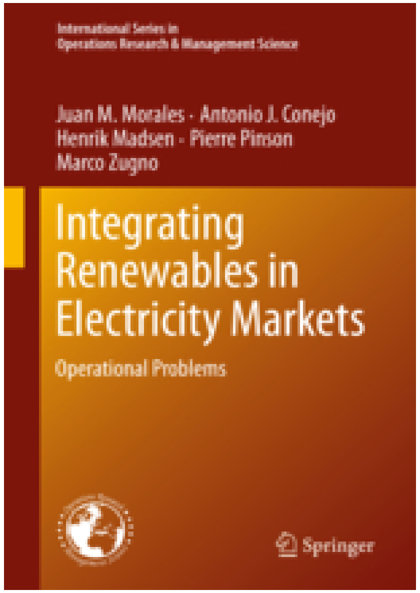
Thanks for your time …

Some 'randomly picked' books on modeling and renewable integration ....







Digitalization Hub - Center Denmark

- A digitalization hub for data intelligent operation of integrated energy systems (electricity, thermal, gas, water)
- A national hub for unlocking the flexibility potential for large scale integration of fluctuating renewable energy
- Tests on framework conditions have to be representative – and scaling is important
- The new national smart energy hub is Center Denmark (10.000 m2 facilities for Research, Education, Development and Testing - plus Dissemination)
- The Societal objective is to establish a realistic and concrete pathway to a fossil-free society
- The Scientific objective is to establish methodologies and solutions for the future intelligent and integrated energy system using digitalization and a smart energy hub
- The Commercial perspective is to being able to idenfy and test solutions which can form the background for commercial success stories. We believe that this setup has the unique characteristics for being the ultimate smart energy hub for test and demonstration of future smart energy solutions