Grey-box identification could benefit model-based control solutions in power plant processes

Further development of methods and software tools are however needed

Jonas Funkquist, Vattenfall R&D

2012-05-16 LCCC 2nd Industrial Workshop, Lund

VATTENFALL

Content

- Vattenfall in brief
- Grey-box identification
- One current modelling driver
- Power plant examples
- Need for grey-box tools
- Conclusions

Content

- Vattenfall in brief
- Grey-box identification
- One current modelling driver
- Power plant examples
- Need for grey-box tools
- Conclusions

Our markets and our position in Europe

Owned by the Swedish state

38,000 employees

Offshore wind power no. 2
955 MW on land
772 MW offshore

Hydro power no. 3
34.6 TWh

Biomass no. 5
1 TWh

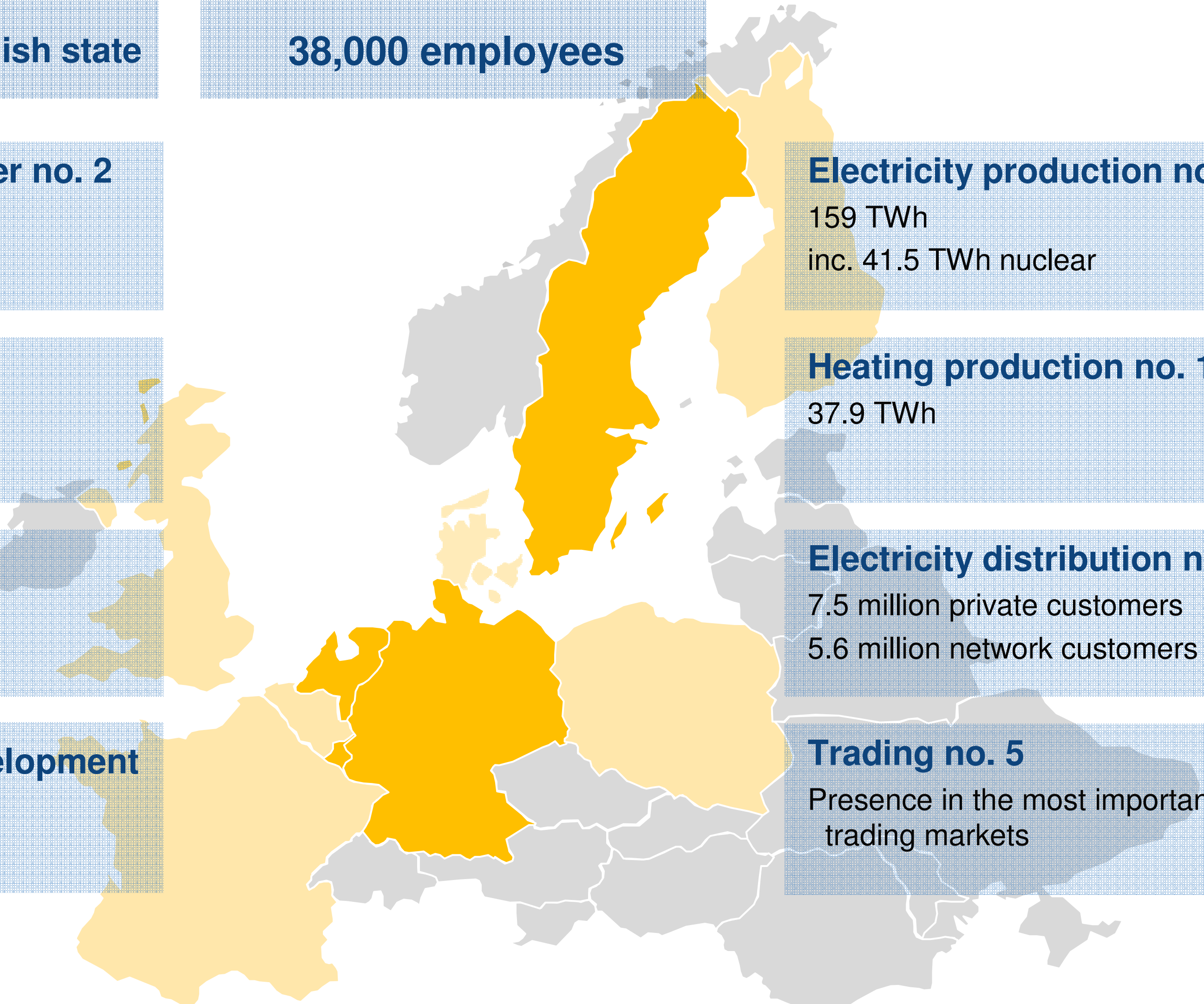
Technological development
Wave energy & CCS

Electricity production no. 6
159 TWh
inc. 41.5 TWh nuclear

Heating production no. 1
37.9 TWh

Electricity distribution no. 6
7.5 million private customers
5.6 million network customers

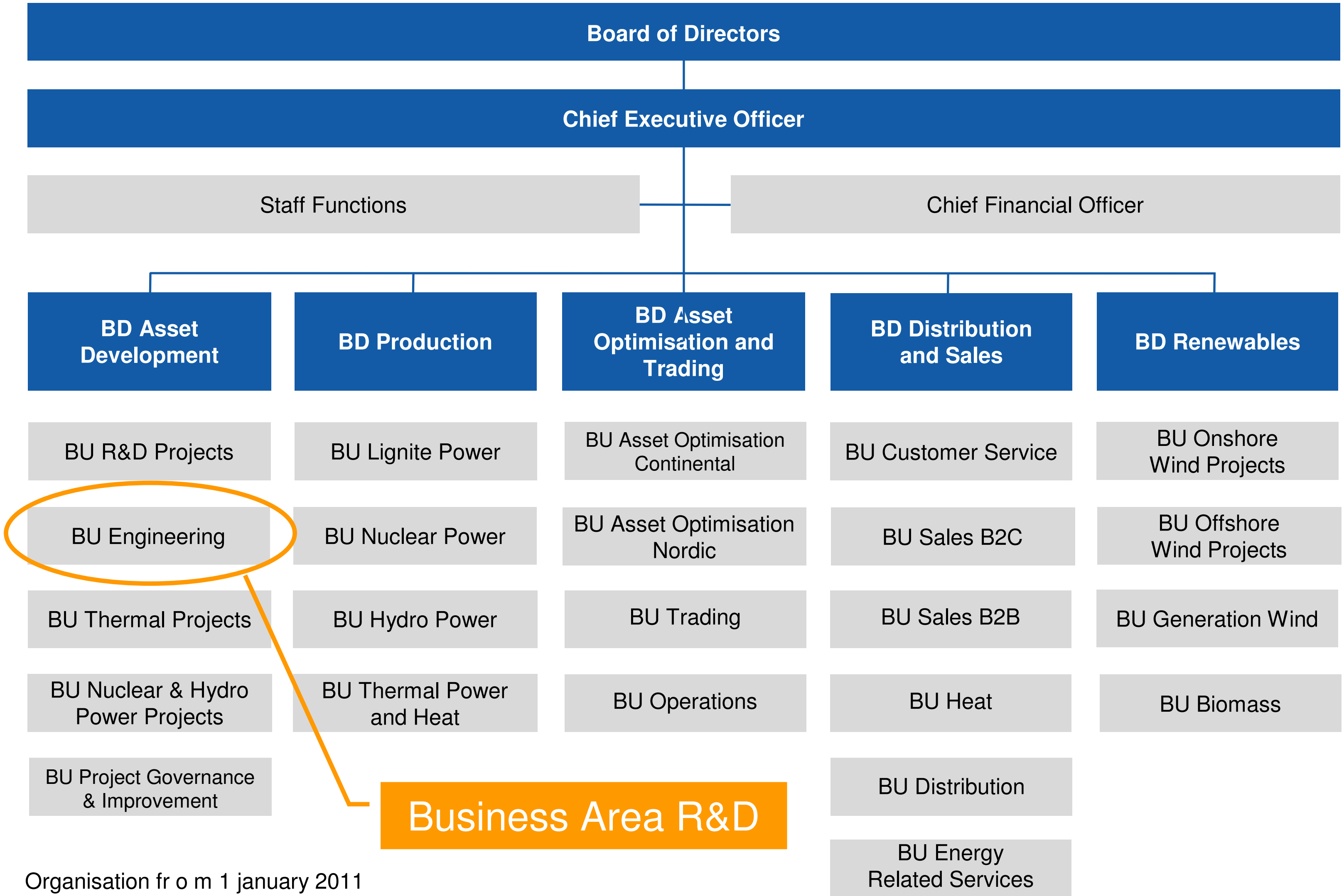
Trading no. 5
Presence in the most important trading markets



Core markets

VATTENFALL

Functional organisation

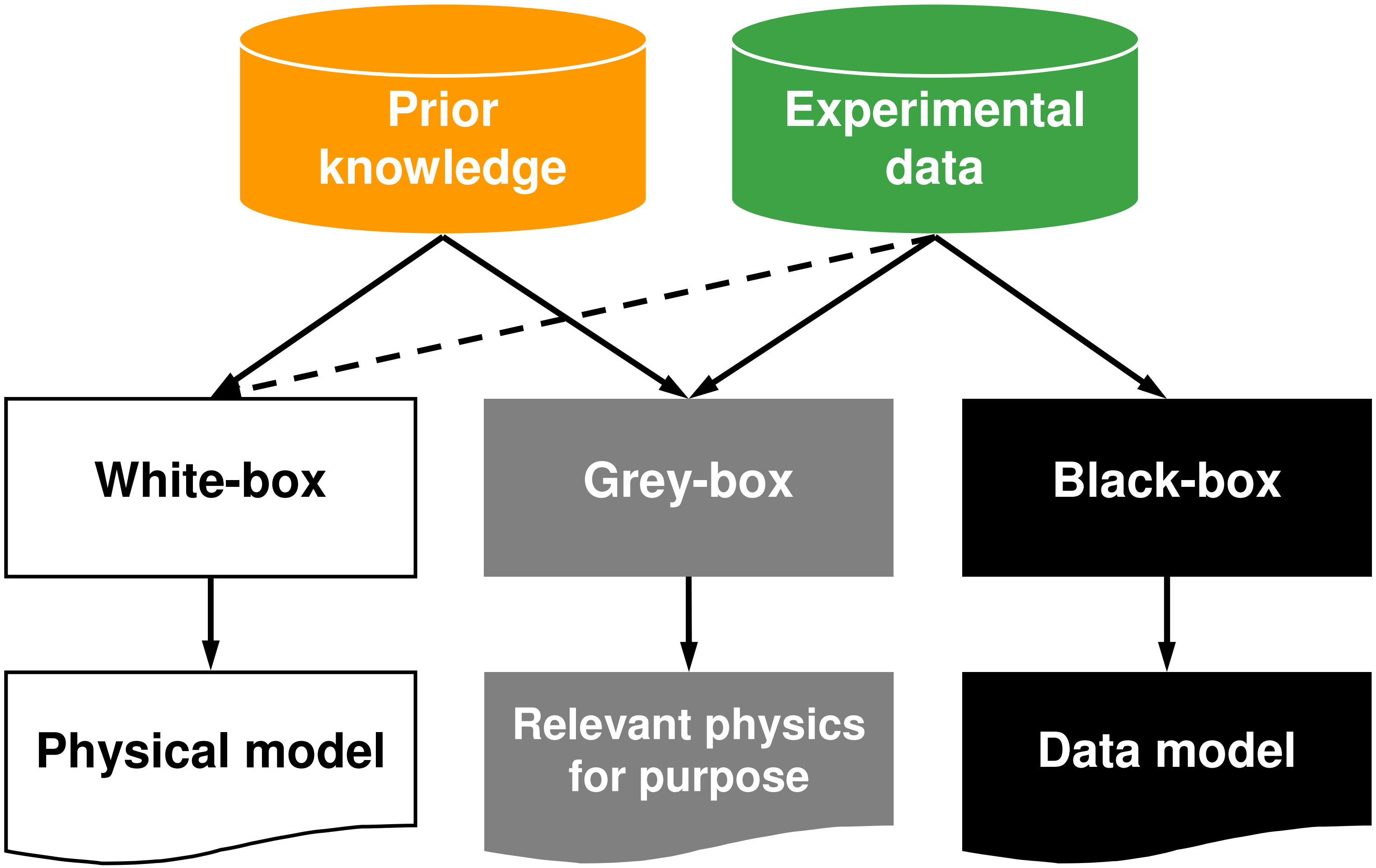


Organisation fr o m 1 january 2011

Content

- Vattenfall in brief
- Grey-box identification
- One current modelling driver
- Power plant examples
- Need for grey-box tools
- Conclusions

Different modelling approaches



VATTENFALL

Grey-box identification – Comparison with white-box and black-box

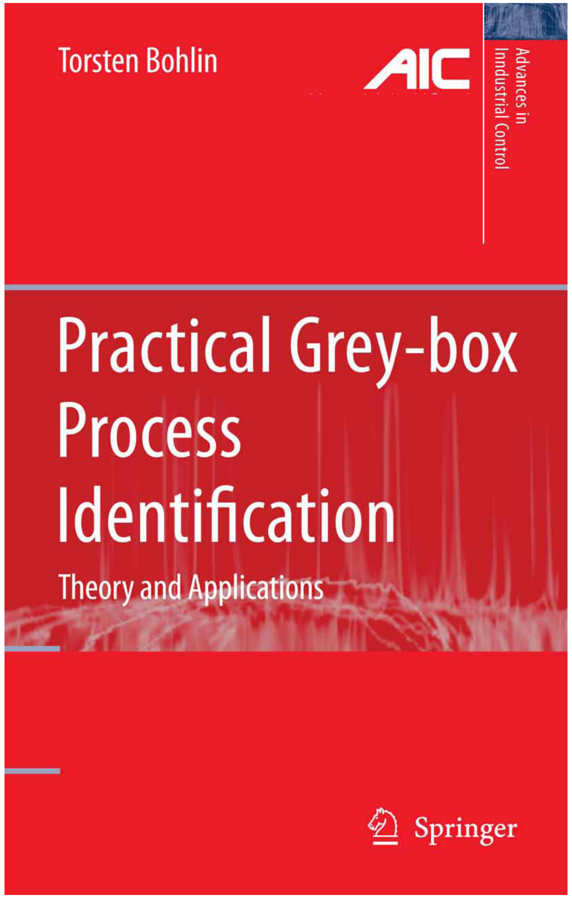
	White-box	Grey-box	Black-box
Using prior knowledge (first principles)	YES	YES	NO
Using experimental data *for model calibration**	NO	YES	YES
Handling of unknown and random effects	NO	YES	YES
Handling of nonlinear systems	YES	YES	YES/NO
Physical interpretation of internal states	YES	YES	NO
Reproducibility (for complex cases)	HIGH	MEDIUM	LOW
Requirement on user expertise	HIGH	HIGH	LOW

* Model calibration also includes model structure selection.
Experimental data are used for parameter estimation in all approaches.

VATTENFALL

Grey-box identification – Some basic questions

- How …
  - … can I make use of what I do know about the process?
  - … much of my prior knowledge is useful, or even correct?
  - … should disturbances, that cannot be eliminated, be handled?
  - … do I know if my experimental data are sufficient and relevant?
  - … do I know when the model is good enough?



Book by Torsten Bohlin
Springer, 2006

Systematic identification method for grey-box identification

- Use a combination of physical models and black-boxes
- *Gradually extend* the model while testing statistical significance against experimental data
- Model calibration
  - Goal: Find simplest model that cannot be falsified
  - Start with a *root model* and extend gradually
  - For each extension, fit free parameters to data
  - Compute statistical risk of rejecting previous model
- Model validation
  - Test the model for a specific purpose

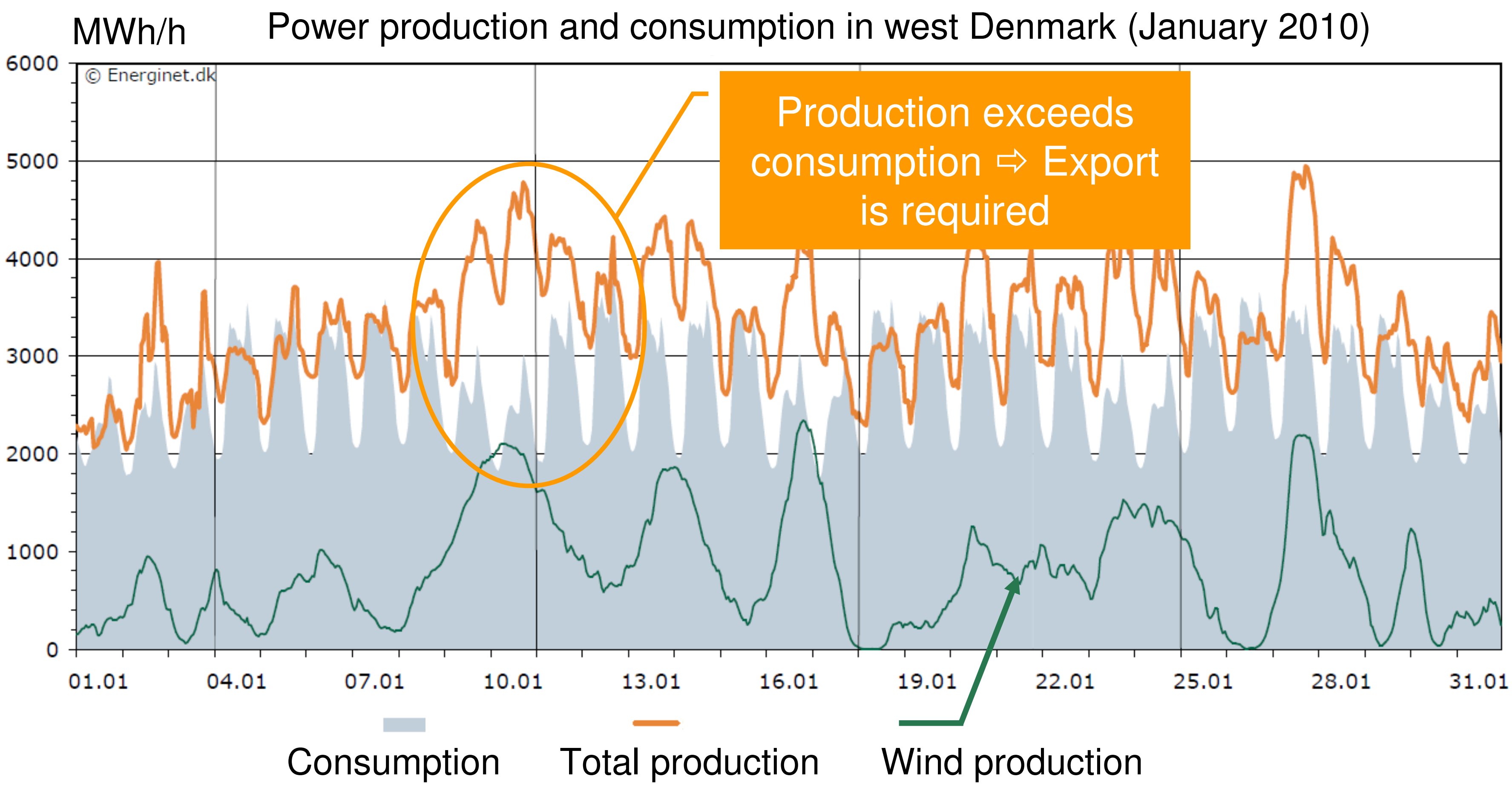
Grey-box identification – Some tools

- MoCaVa (Torsten Bohlin)
  - Rigorous base – Based on many years of research
  - Supported model structures: Nonlinear *stochastic* state space models
  - Only basic user interface – though including all major components
  - No current development
- System Identification Toolbox (Matlab)
  - Supported model structures: Nonlinear state space models (not stochastic)
  - Lacking systematic user guidance
  - Integrated in the Matlab "world"
  - …
- CTSM – Continuous Time Stochastic Modelling (DTU, Copenhagen)
  - Supported model structures: Nonlinear *stochastic* state space models
  - Pure parameter estimation, no support for the interactive identification process
  - Very basic GUI
  - Current development? Last version 2005!
- …

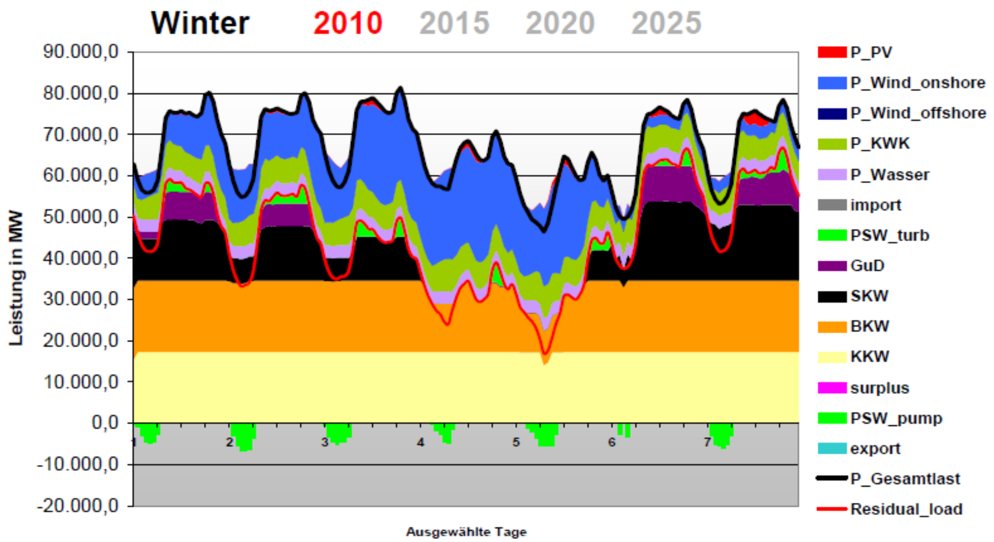
Content

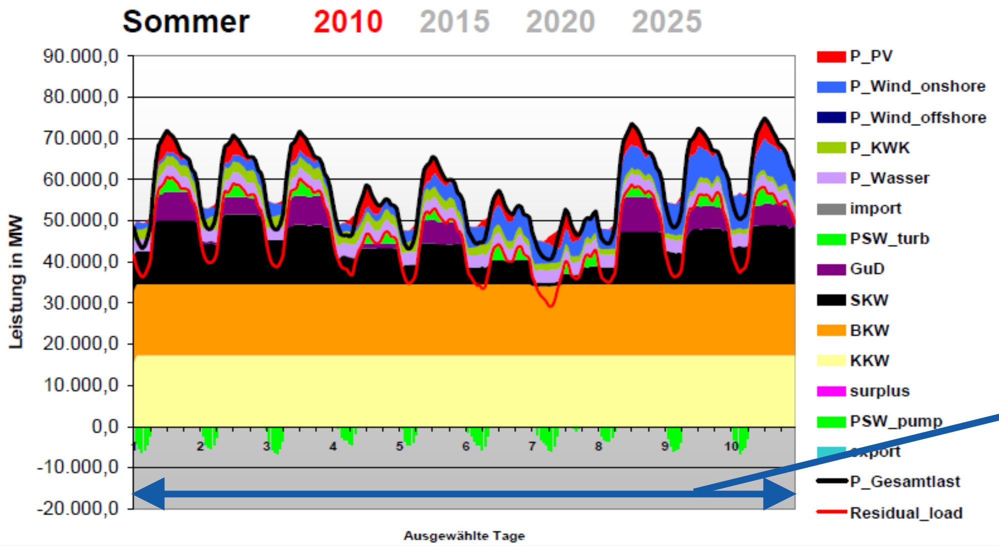
- Vattenfall in brief
- Grey-box identification
- One current modelling driver
- Power plant examples
- Need for grey-box tools
- Conclusions

The market asks for flexibility – Situation in Denmark



Substitution of conventional thermal power plants by CHP and renewables



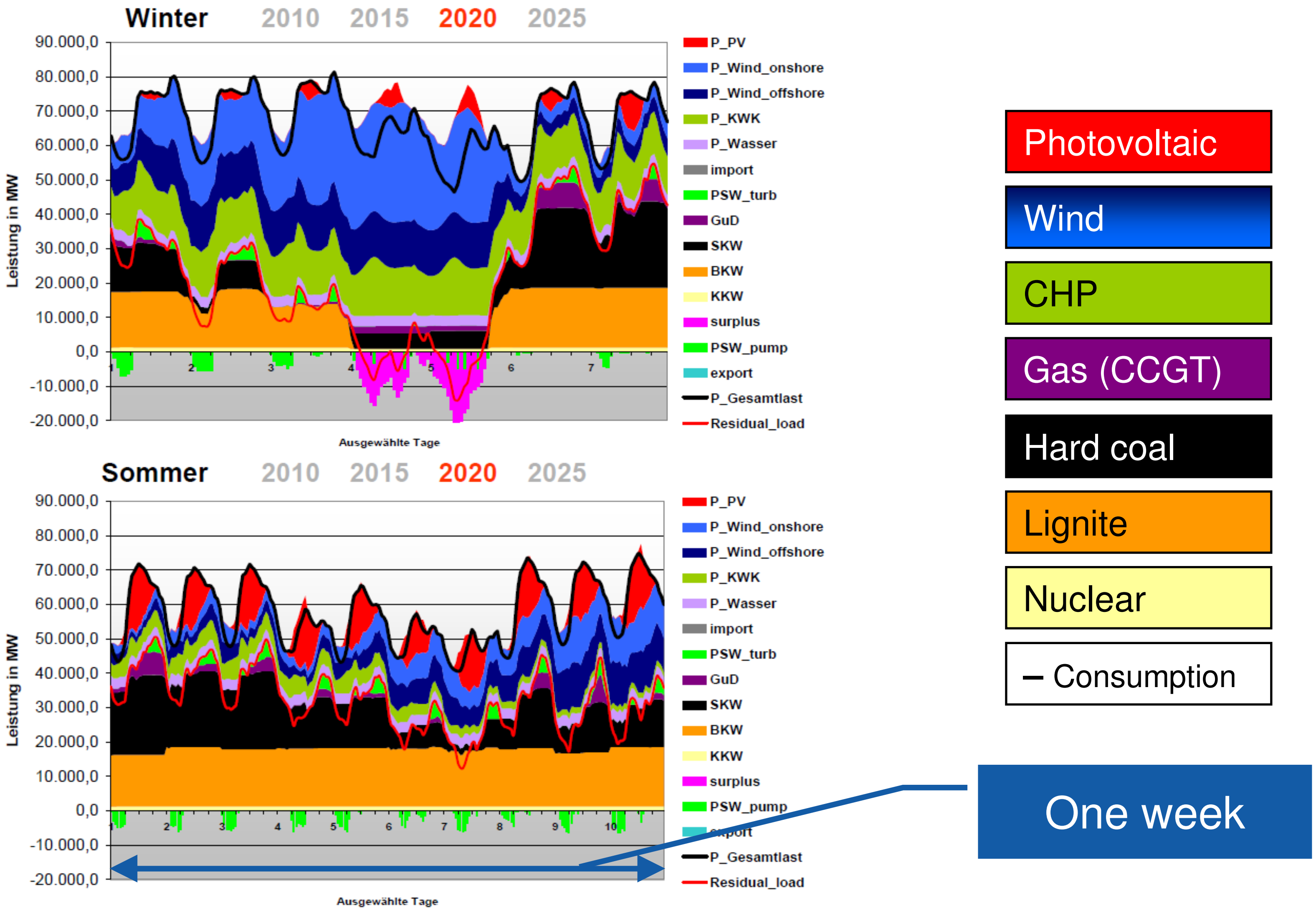


- Photovoltaic
- Wind
- CHP
- Gas (CCGT)
- Hard coal
- Lignite
- Nuclear
- – Consumption

One week

Substitution of conventional thermal power plants by CHP and renewables

Universität Rostock Traditio et Innovatio



VATTENFALL

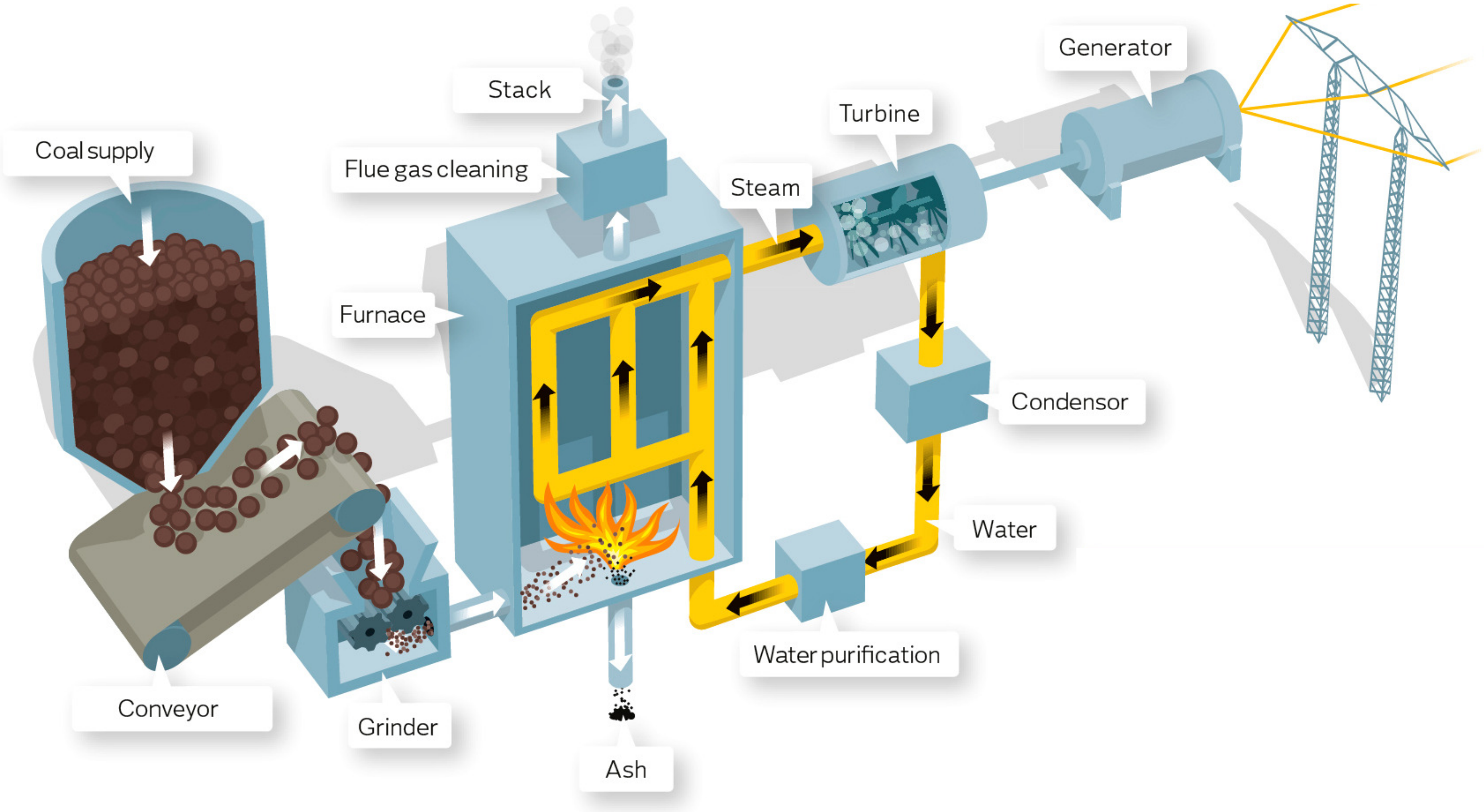
More dynamic operation of thermal power plants

- Flexibility needs
  - Reduction of minimum load
  - Shorten time for start-up and shut-down
  - Increased load change rate
- Problem
  - Most thermal power plants of today are built for base load, optimised for 100 % load
- Consequences
  - Load span between 0 and 40-50 % often not feasible or operated with very low efficiency
  - Start-up and load change rate often limited by thermal stress in components
  - Start-ups are very costly

Content

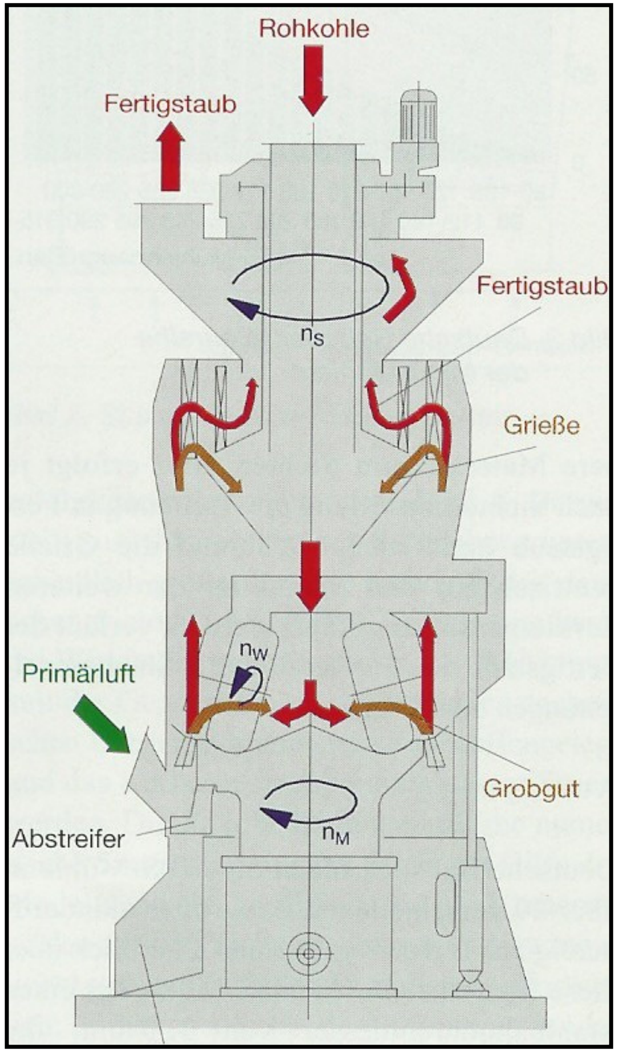
- Vattenfall in brief
- Grey-box identification
- The current modelling driver
- Power plant examples
- Need for grey-box tools
- Conclusions

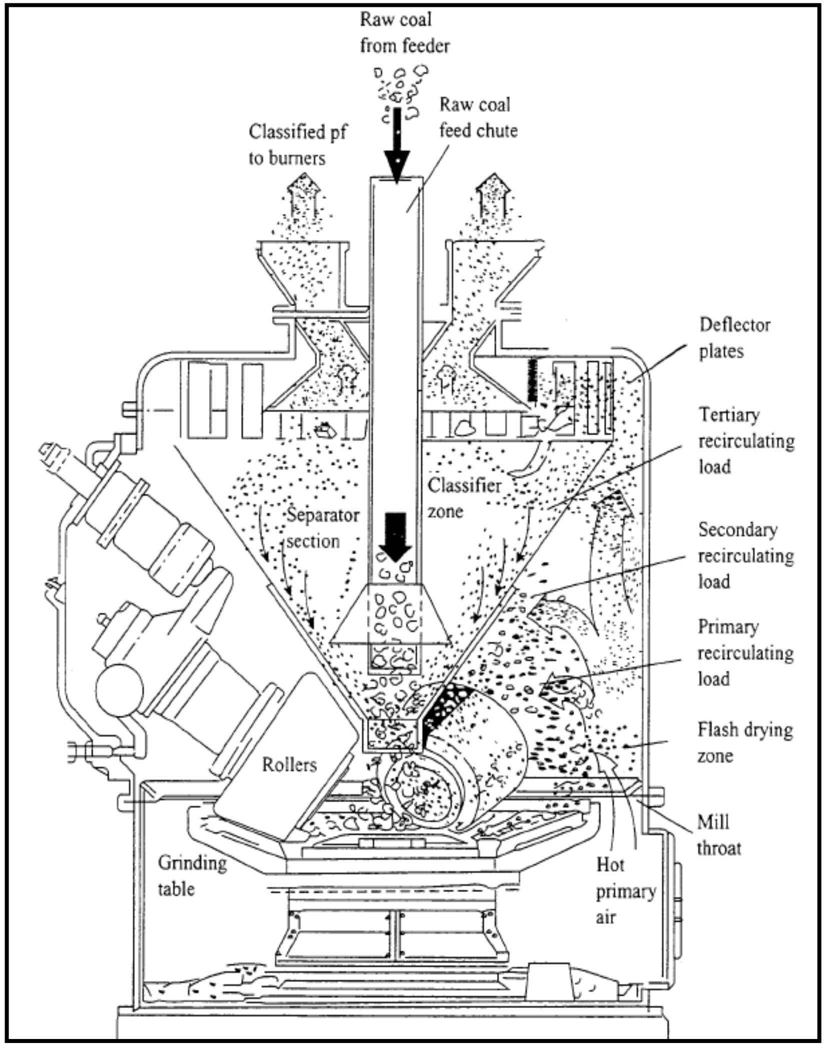
The coal-fired power plant



VATTENFALL

Example 1 – Grey-box identification of the coal mill

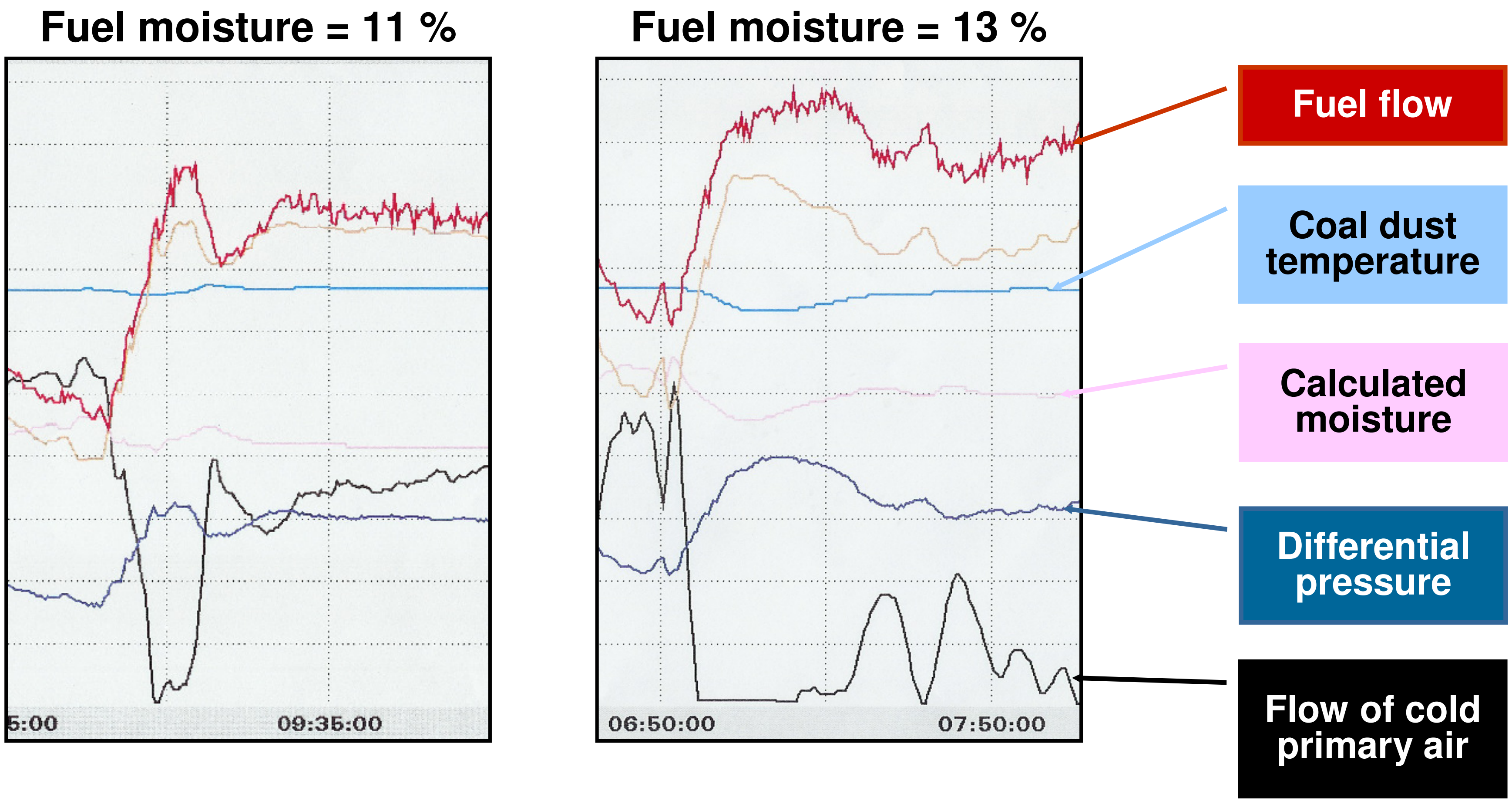




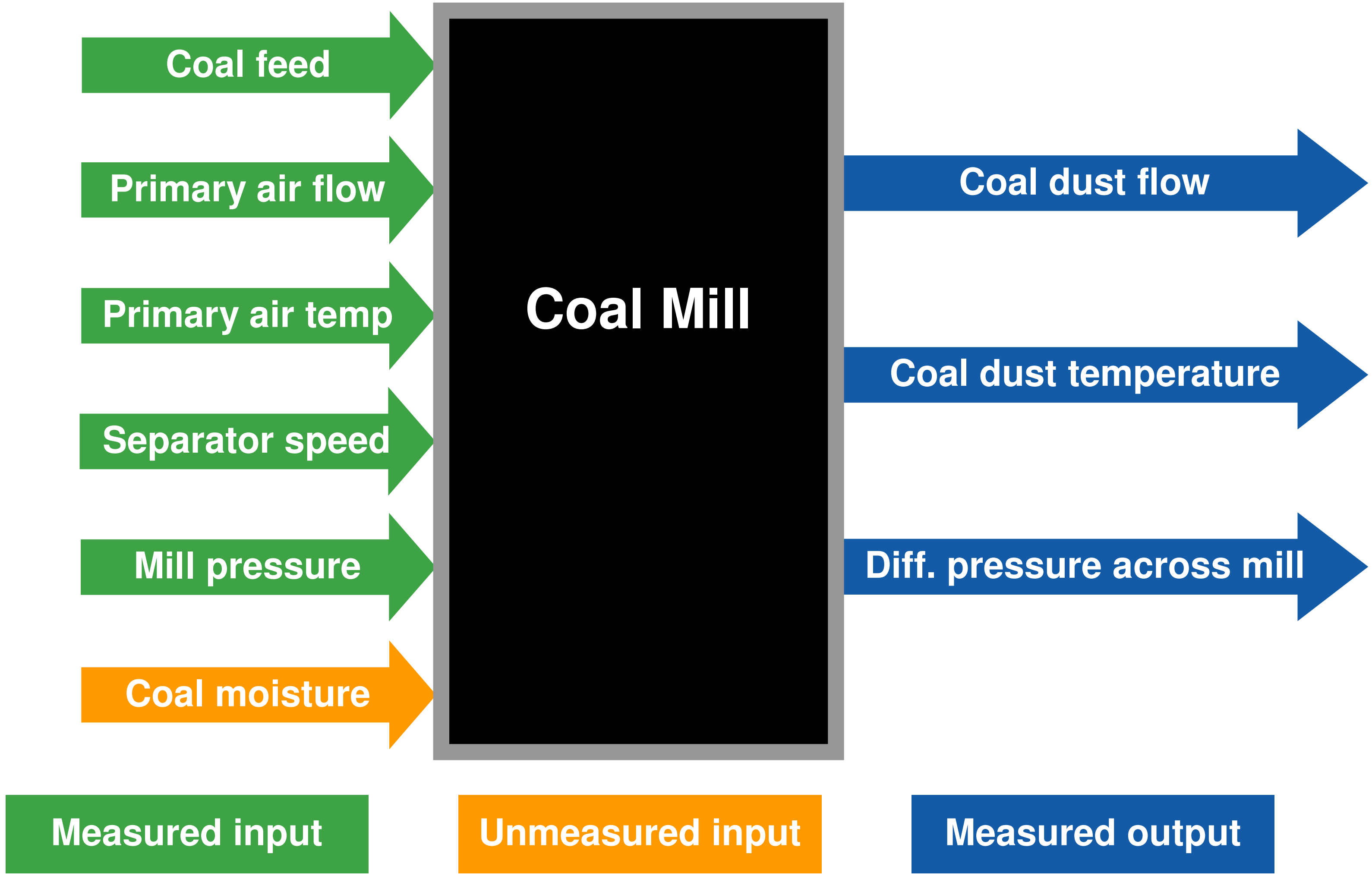
VATTENFALL

Mill response during load increase (15 MW/min)

High level of disturbances and very complex interactions



Mill model – Inputs and outputs

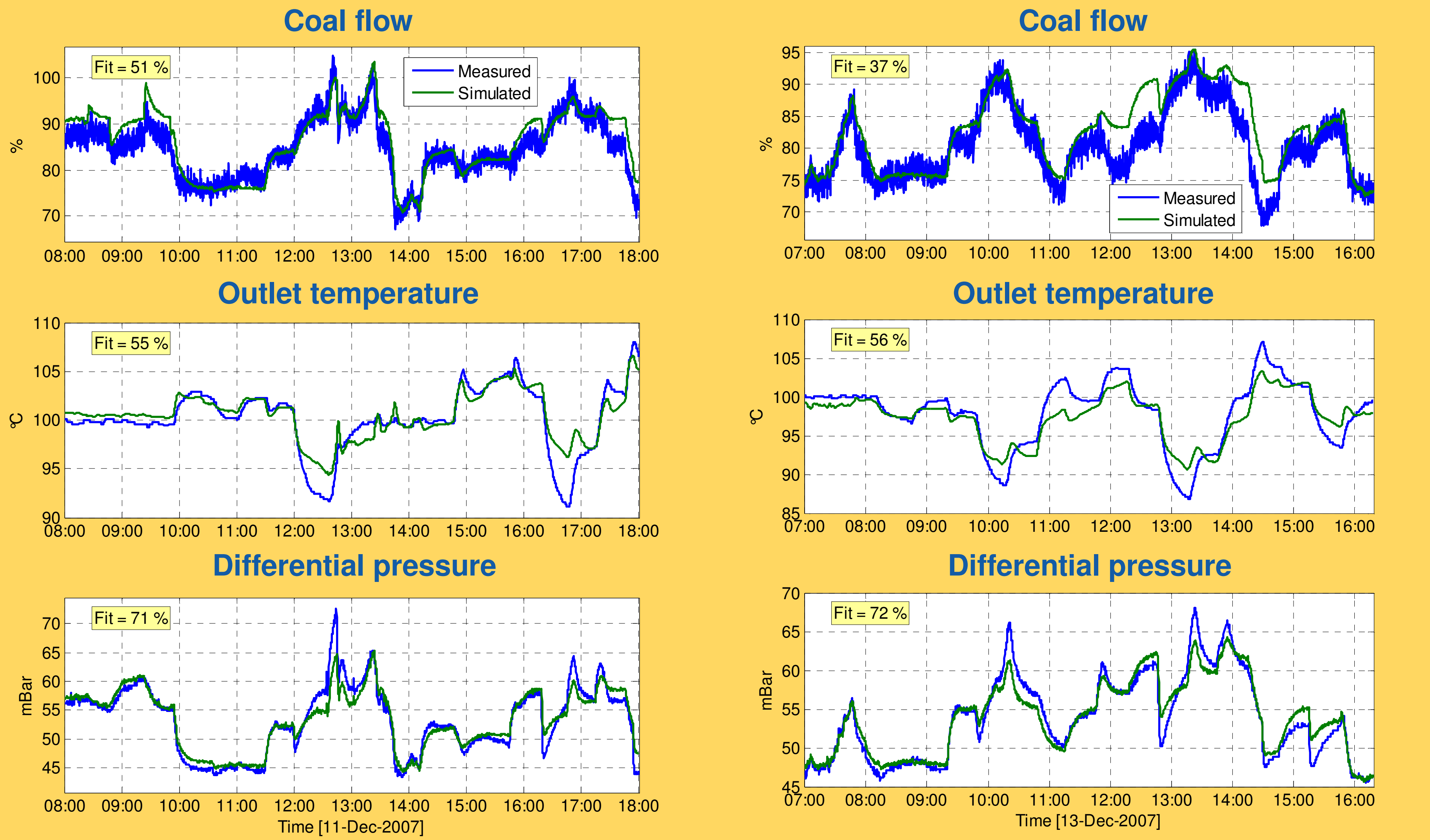


VATTENFALL

Mill model - Identification using MoCaVa

Calibration data

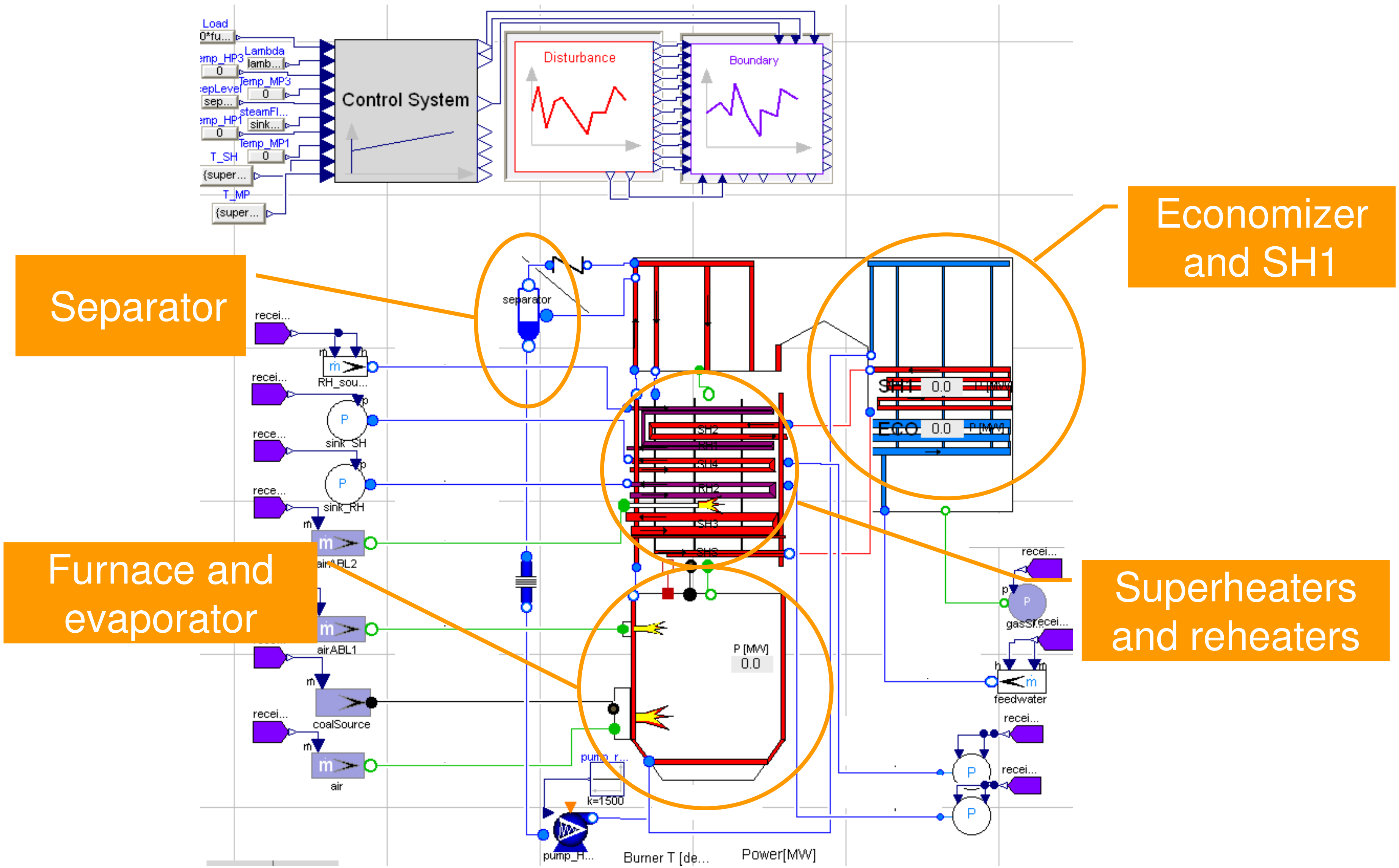
Validation data



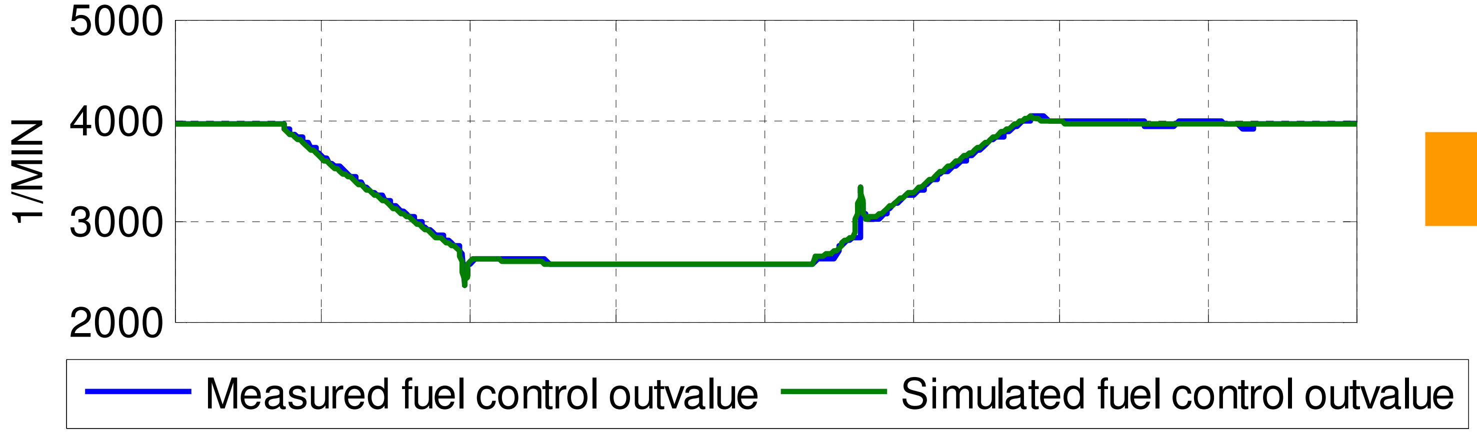
Mill modelling – Lessons learned

- Far much more work to develop model than expected
- Difficult to get process data covering the desired operation range
- The parameter estimation required much trial and error
  - Bad parameter sensitivity and convergence problems
  - Unreasonable parameter values
  - No suggestion on where problem originate:
    - Data, Model structure, Numerical algorithms, …
- Proper functioning of measurement devices crucial
  - The grey-box approach was used to model deficiencies
- No guidance about how to refine the model is given by MoCaVa

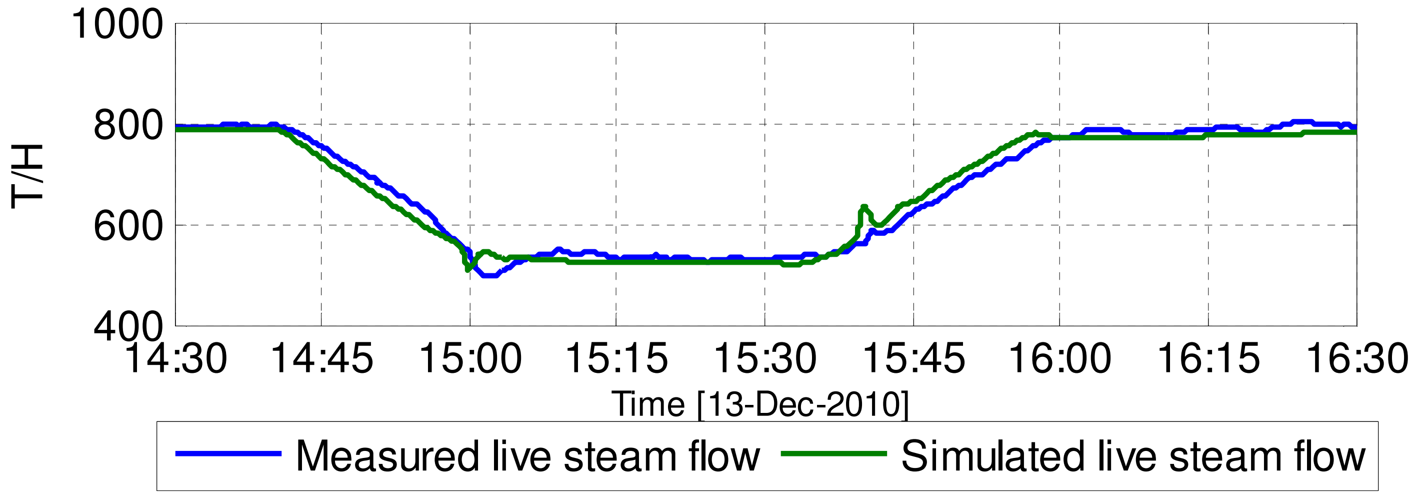
Example 2 – White-box modelling of a lignite fired power plant



Load change – Main input and output



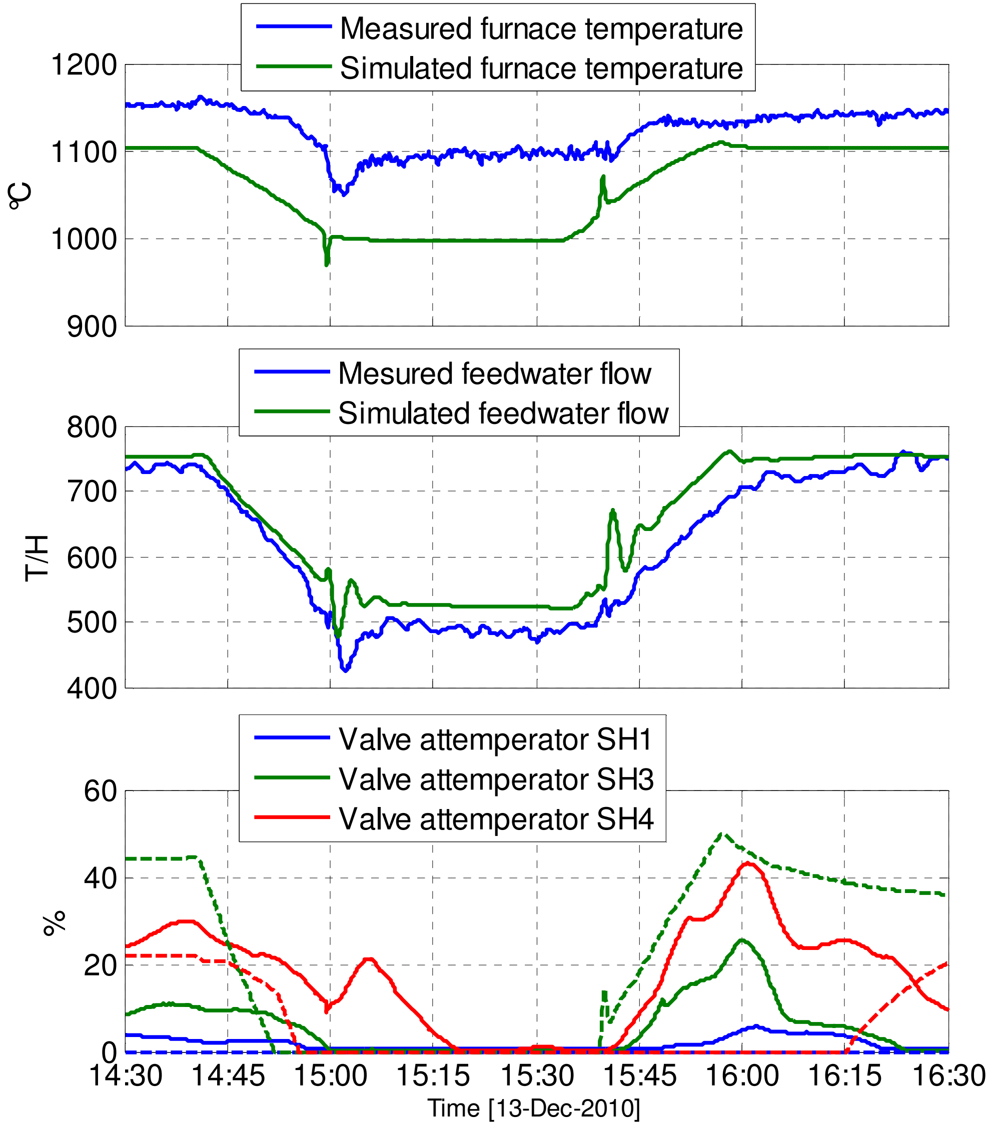
Fuel input



Steam flow

VATTENFALL

Load change – Some process signals

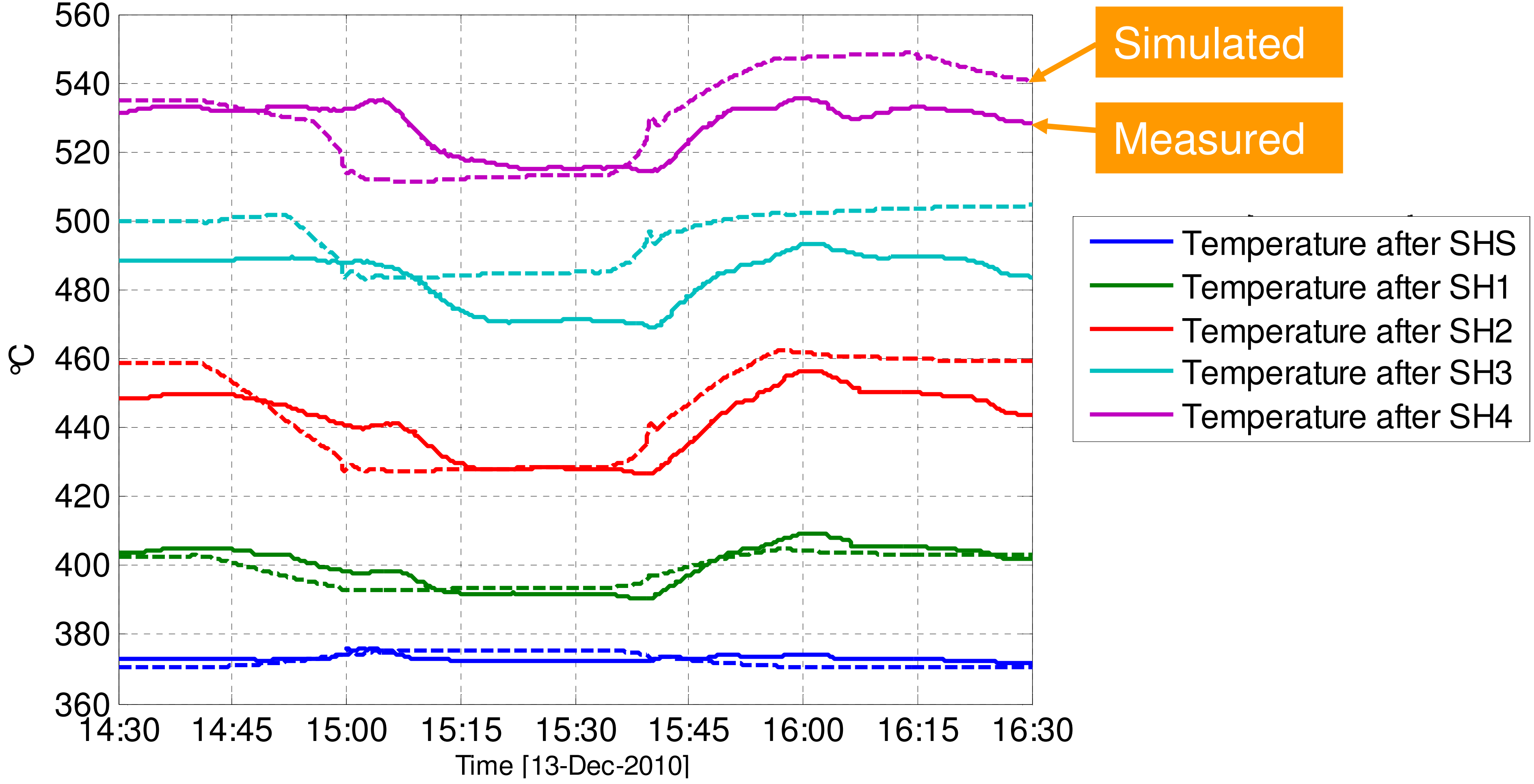


Furnace temperature

Feedwater flow

Spray water valves

Load change – Superheater steam temperatures



Confidentiality - None (C1)

VATTENFALL

Power plant modelling – Lessons learned

- Modelling in Dymola using the CombiPlant library
  - Bottom-up approach resulting in a very detailed and complex model
- Model tuning/calibration
  - Done manually with the complex model as starting point
  - Difficult due to too much degrees of freedom
  - Too “heavy” model to use automatic parameter estimation
- Model simulation
  - Model not robust: Small changes gives often solving problems
- Would a systematic grey-box approach with gradual extension have resulted in a more robust and accurate model?
  - Yes, I believe so!

Content

- Vattenfall in brief
- Grey-box identification
- The current modelling driver
- Power plant examples
- Need for grey-box tools
- Conclusions

Why Grey-box identification?

- Model-based solutions for optimisation and control depend on good models
- Model development often consumes a major part of the development time for such solutions
- A fully developed grey-box identification method would facilitate the trade off between model complexity and quality
- We need a systematic method to handle high complexity and high level of disturbances (including nonlinear models)

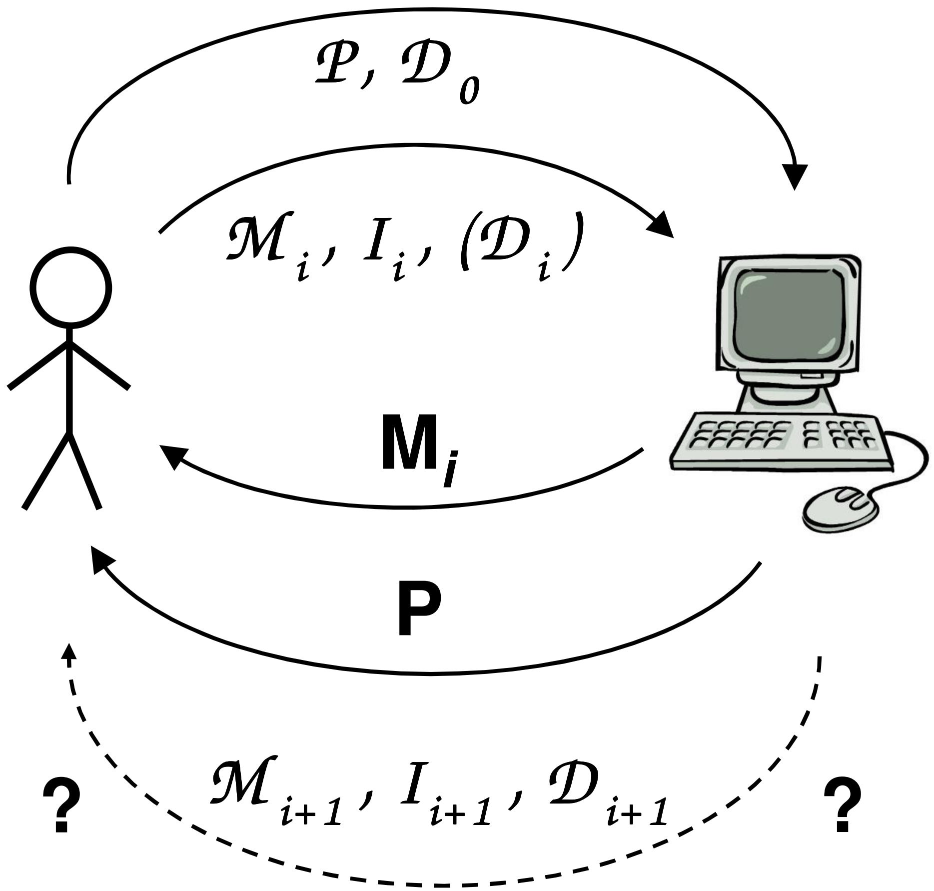
- Grey-box identification …
  - … aims to find the simplest model that fits the purpose for the model
  - … may include disturbance models to account for unmeasured inputs and states as well as unmodelled phenomena

The interactive procedure of grey-box identification

$\mathcal{P}$ – Model purpose
$\mathcal{M}$ – Model structure
$\mathcal{I}$ – Initial parameters
$\mathcal{D}$ – Process data
P – Purpose fulfilled
M – Model candidate

User

- Model structure specification
- Initial parameters
- Process data
- …



Software tool

- Model construction
- Predictor simulation
- Identifiability checking
- Model selection
- Model validation
- …

VATTENFALL

Grey-box identification – Some difficulties

- Heavy computing
  - Nonlinear stochastic models in the context of system identification gives computing intensive algorithms
- Interactive
  - High degree of interactivity ⇨ Hard to do heavy computing overnight
- Failures
  - More freedom in model structure specification increases risk for failures
- Stopping
  - Test criteria for stopping depends very much on the users ability to specify tentative model structures ⇨ Risk that wrong model passes!
- Too much stochastics
  - Stochastic models gives good prediction models (at least for short range) and may tempt the user to use too much stochastics ⇨ Risk for worse reproducibility than necessary!

Content

- Vattenfall in brief
- Grey-box identification
- The current modelling driver
- Power plant examples
- Need for grey-box tools
- Conclusions

VATTENFALL

Conclusions

- More dynamic operation of power plants will be required in the future due to a larger share of intermittent power production
- Model-based optimisation and control solution may facilitate this change
- This process is, however, slowed down since effective methods for creating predictive models are still lacking
- The grey-box identification methodology represents an attractive alternative to trade off complexity and quality
- Even though research has been going on for decades in this area, easy to use tools are still missing and work is needed both regarding fundamental algorithms and practical “how to” guides


The End