

The impact of different PV module configurations on balancing needs of a highly renewable European power system

Kabitri Chattopadhyay¹, Alexander Kies^{1,2},
Elke Lorenz³, Lüder von Bremen¹, Detlev Heinemann¹

¹Carl von Ossietzky University, Oldenburg, Germany

²Frankfurt Institute for Advanced Studies FIAS, Frankfurt, Germany

³Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany

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Rapid transformation of European power grid to allow high shares of renewable energy sources:

- ▶ to mitigate climate change
- ▶ to avoid dependence on fast depleting fossil fuels

Model design

Model designed for a future European power system with high shares from variable solar and wind resources to understand the impact of PV module orientation and inclination of the balancing needs.

Background

Research questions



- ▶ How the variable nature of major renewables affect balancing needs on different time scales?
- ▶ Which factors determine the ability of a module configuration to best match the load curve?
- ▶ Why the South facing optimally inclined (SFOI) modules are not always optimal in reducing balancing?

Model overview

Data sources



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Project: RESTORE 2050

Meteorological data

- ▶ Solar irradiance from Meteosat satellites
- ▶ Wind speed and temperature from NWP models

Load data from ENTSO-E

- ▶ average hourly load (av.h.l.): 404.2 GWh
- ▶ average annual load (av.a.l.): 3543.3 TWh

Model details

- ▶ Domain: 33 European countries
- ▶ Resolution: Spatial 7×7 km, temporal 1 hour
- ▶ Simulation period: 2003 - 2012

Model overview

Balancing simulation



The key parameter here is the mismatch:

$$\Delta(t) = \alpha G(t) - L(t)$$

$$\Delta(t) = \Delta_+(t) + \Delta_-(t)$$

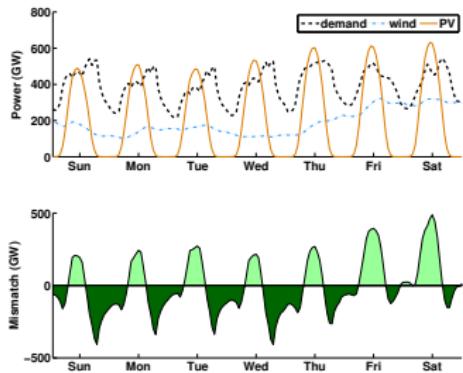
Residual load (Δ_-) determines balancing:

$$E_b = \langle \Delta_- \rangle / \langle L \rangle$$

$$E_b^{add} = E_b - (1 - \alpha)_+$$

Note:

- ▶ α : Average variable renewable energy (VRE) generation factor
- ▶ β : Solar share



Model overview

Storage simulation



Conversion losses in storage: $\tilde{\Delta}(t) = \eta_{in}\Delta_+(t) + \eta_{out}^{-1}\Delta_-(t)$

Storage filling is influenced by α , η_{in} , η_{out} , and given by:

$$F(t) = \begin{cases} C_s & \text{for } F(t-1) + \tilde{\Delta}(t) > C_s \\ 0 & \text{for } F(t-1) + \tilde{\Delta}(t) < 0 \\ F(t-1) + \tilde{\Delta}(t) & \text{otherwise} \end{cases}$$

Storage capacity (C_s) is defined as:

$C_s = \max_t(F(t)) - \min_t(F(t))$, for a lossless storage with $\alpha = 1.0$

$C_s = \max_t(F(t) - \min_{t' \geq t}(F(t'))$, when storage builds up over time

$C_s = \max_t(F(t) - \min_{t' \leq t}(F(t'))$, when storage depletes over time.

Model overview

Module configurations

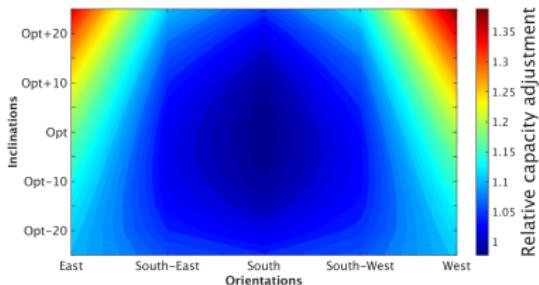


55 separate configurations are analyzed.

inclinations opt $\pm 25^\circ$
 opt $\pm 20^\circ$
 opt $\pm 15^\circ$
 opt $\pm 10^\circ$
 opt $\pm 5^\circ$
 optimal

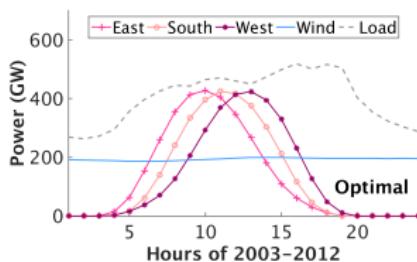
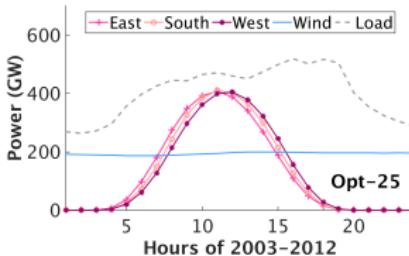
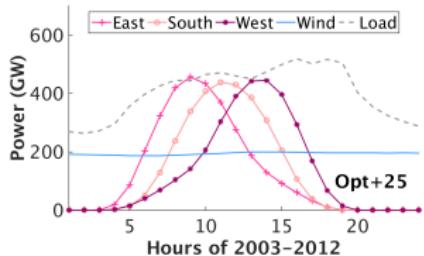
orientations East
 South-East
 South
 South-West
 West

Capacity adjustment relative to the time series of a realistic distribution of mixed configurations:



Variability characteristics

Diurnal patterns

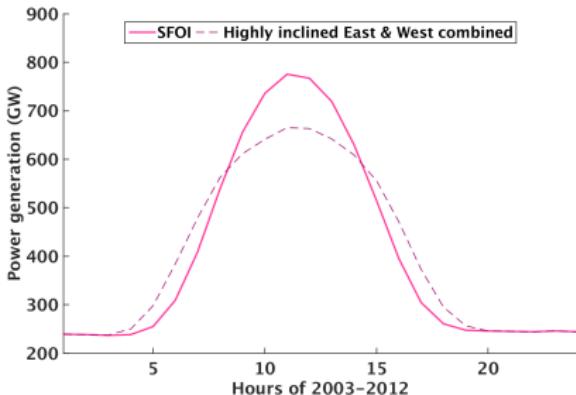


Highly inclined West facing modules best match diurnal load curve.
(Time series for solar share 40% with time frame 2003-2012.)

Variability characteristics

Combined configuration

Combining highly inclined East and West facing modules.



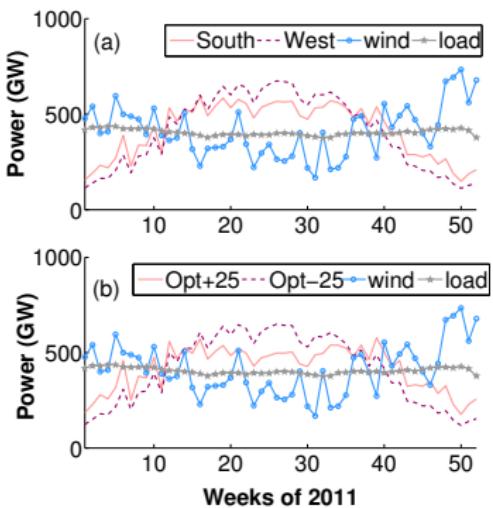
In a scenario with $\alpha = 1.0$ and $\beta = 0.4$

- ▶ West facing opt+25° reduces balancing 1.8% for capacity increase 41.9%
- ▶ combined opt+25° reduces balancing 11.3% for capacity increase 40.1%

SFOI: South facing optimally inclined

Variability characteristics

Seasonal patterns



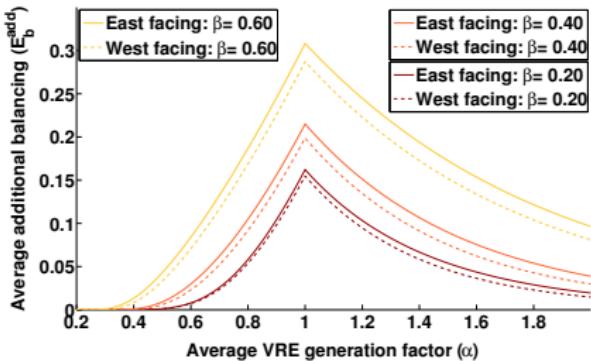
Wind and PV power are each scaled to the average load.

Preferred configuration:

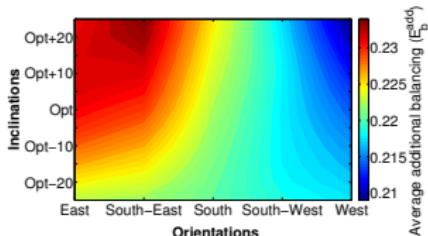
- ▶ highly inclined South facing modules (PV dominated scenario)
- ▶ lowly inclined East and West facing modules (wind dominated scenario)

Balancing needs

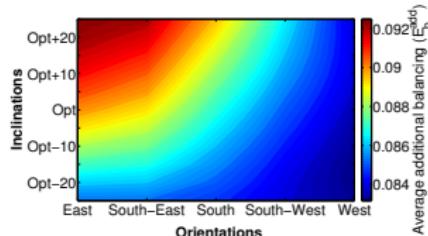
Scenario-1: Balancing in absence of storage



Module inclinations (optimal+25°)



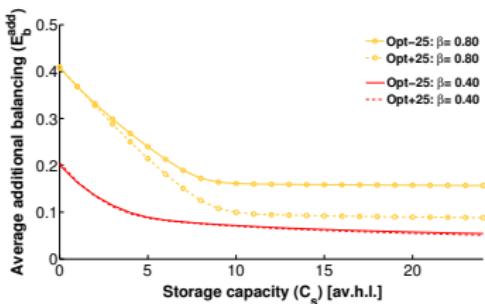
$$\alpha = 1.25, \beta = 0.6$$



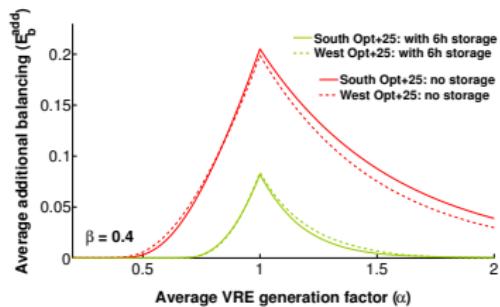
$$\alpha = 1.25, \beta = 0.2$$

Balancing needs

Scenario-2: Balancing in presence of a constrained storage



Modules facing South



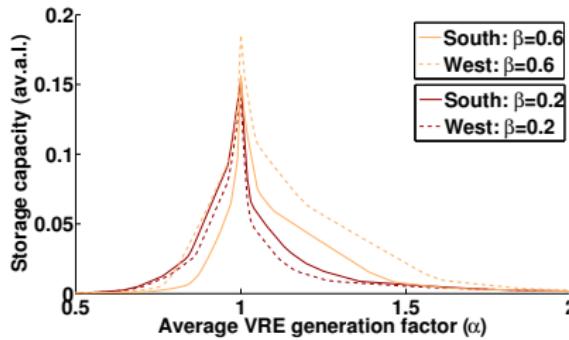
Solar share $\beta = 0.4$

Governing factors:

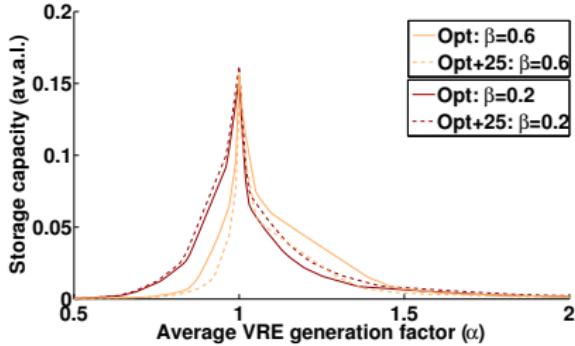
- ▶ below the threshold: diurnal patterns of load and generation
- ▶ above the threshold: seasonal patterns of load and generation

Balancing needs

Scenario-3: Unlimited storage to completely avoid average additional balancing



Optimally inclined modules



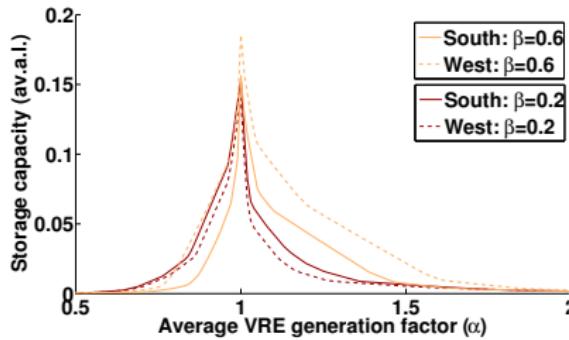
South facing modules

PV dominated scenario ($\beta = 0.6$): South facing Opt+25°:

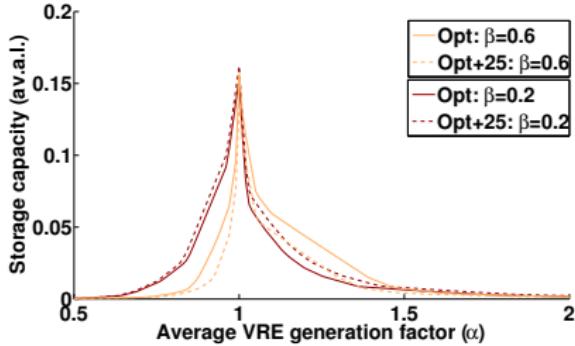
- ▶ 12.2% reduction compared to SFOI ($\alpha = 1.0$)
- ▶ 36.1% reduction compared to SFOI ($\alpha = 1.25$)

Balancing needs

Scenario-3: Unlimited storage to completely avoid average additional balancing



Optimally inclined modules



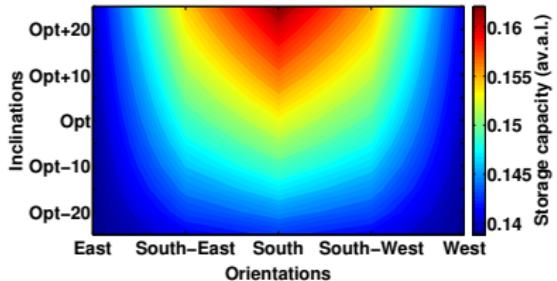
South facing modules

Wind dominated scenario ($\beta = 0.2$): West facing Opt-25°:

- ▶ 9.1% reduction compared to SFOI ($\alpha = 1.0$)
- ▶ 37.5% reduction compared to SFOI ($\alpha = 1.25$)

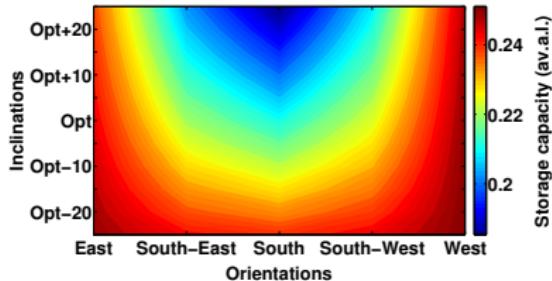
Balancing needs

Scenario-3: Unlimited storage to completely avoid average additional balancing



Wind dominated scenario ($\beta = 0.2$)

$$\eta_{in} = \eta_{out} = 1.0, \alpha = 1.0$$



PV dominated scenario ($\beta = 0.8$)

Preferred configurations:

- ▶ lowly inclined East and West facing modules (β low)
- ▶ highly inclined South facing modules (β high)

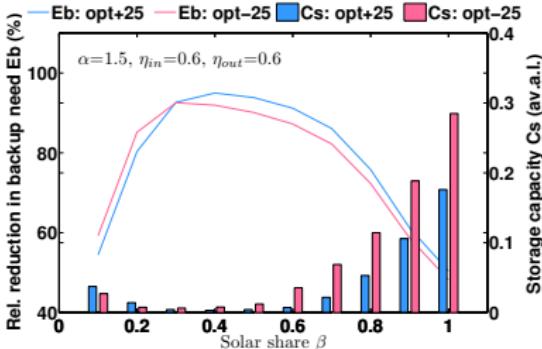
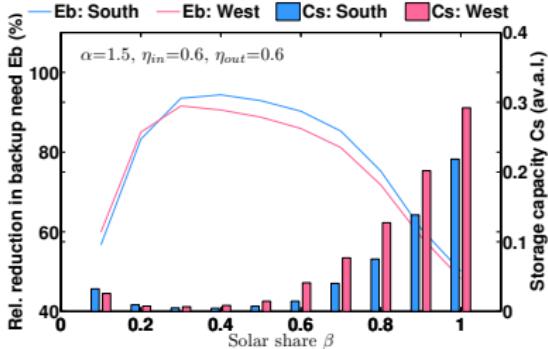
Balancing needs

Scenario-4: Two storage scenario

- ▶ First use a high efficiency ($\eta_{in} = \eta_{out} = 1.0$) small 6 hour storage.
- ▶ Then use a seasonal hydrogen ($\eta_{in} = \eta_{out} = 0.6$) storage.

Dispatch strategy

All excess generation is directed to the smaller storage, until it is full
All residual load is balanced from the smaller storage, until it runs empty.



Conclusion

Summary & outlook



Key findings:

- ▶ Favorable module configuration is very sensitive to solar and wind shares.
- ▶ If a storage is available, highly inclined modules are preferred in high β scenarios.
- ▶ Lowly inclined East/West modules are favorable in wind dominated scenarios.
- ▶ If no storage available, a combination of highly inclined East and West facing modules are preferred.

Thank you all for your attention!

Our sincere thanks to

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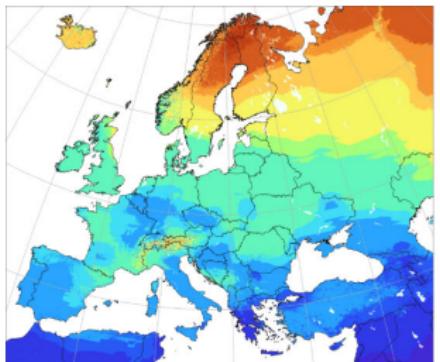
Contact: kabitri.chattopadhyay@uni-oldenburg.de

Under clear-sky conditions

preferred inclinations similar to local latitudes

Under cloudy conditions

lowly inclined modules are preferred



configurations Contribution

opt $\pm 10^\circ$	5%
opt $\pm 5^\circ$	20%
optimal	50%
South-East	20%
South	60%
South-west	20%