Impact of power production from different module configurations on PV fluctuations and storage requirements

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GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

ENERGIESPEICHER
Forschungsinitiative der Bundesregierung

Overview

- Background
- Analysis of fluctuation
- Analysis of storage
- Summary and outlook

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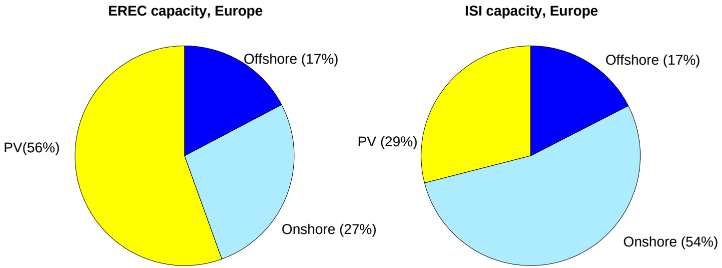
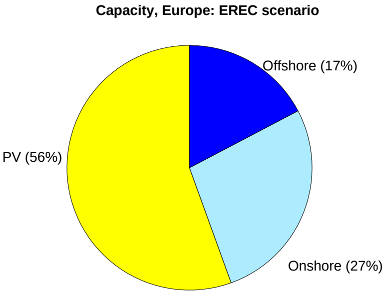
Objective

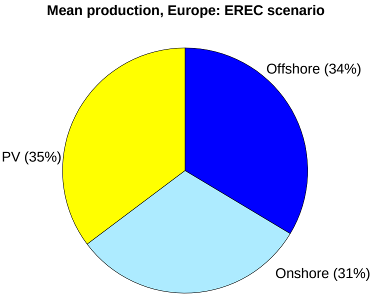
- impact of different module configurations on PV fluctuations and storage needs
- analysis on different temporal scales (hourly, daily, weekly, monthly)



Since this analysis is focused on the PV variability, we chose the EREC scenario as it has high PV share compared to ISI.

Scenario overview





Overview of chosen EREC scenario for Europe

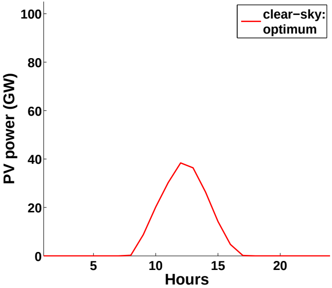
For the original RESTORE-2050 timeseries, share of different module configurations taken from meta-study ISI

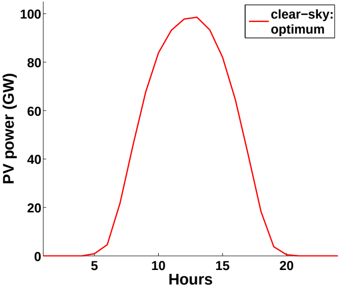
Parameter	**Configuration**	**Share**
Orientation	South-East	20%
	South	60%
	South-West	20%
Inclination	$Opt - 10^\circ$	5%
	$Opt - 5^\circ$	20%
	Opt	50%
	$Opt + 5^\circ$	20%
	$Opt + 10^\circ$	5%

Two effects determine module inclinations for maximum production:

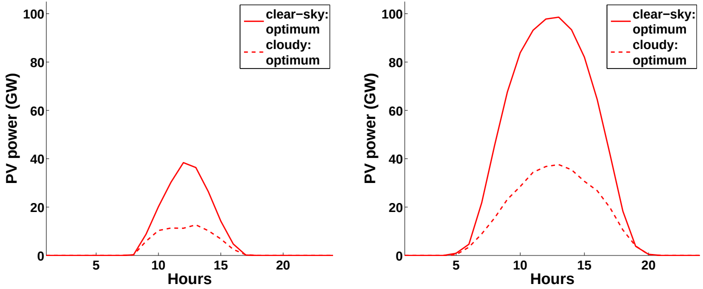
- for clear-sky conditions, module inclinations are similar to local latitudes
- for cloudy conditions, lower inclinations are preferred

Depending on location and season, solar elevation is different and so is the preferred inclination.





PV power production from south facing modules shown for example days in different seasons (left: January, right: July) for Germany



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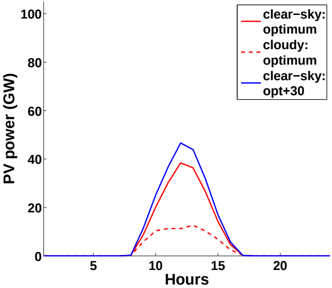

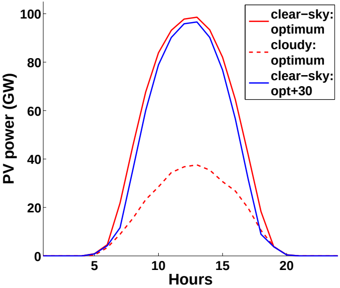

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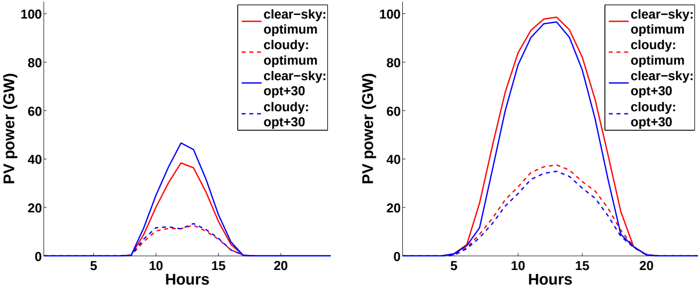

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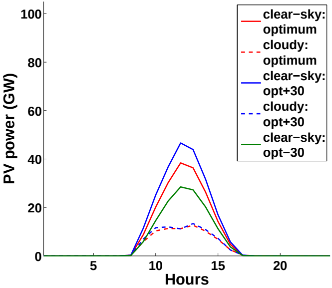

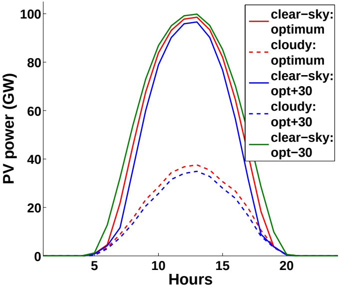

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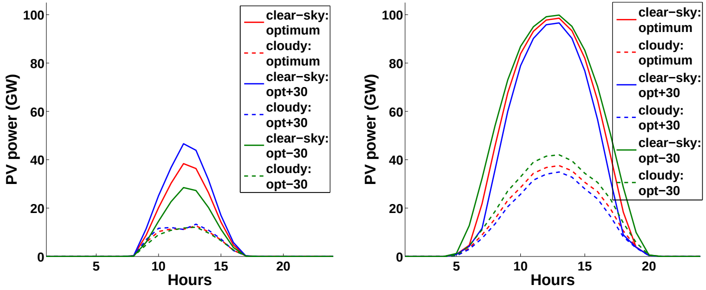


PV power production from south facing modules shown for example days in different seasons (left: January, right: July) for Germany

Existing studies have optimal module inclinations for best PV power production.

We extended this to quantify PV fluctuations on different module configurations.

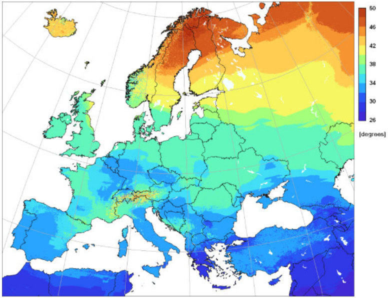


Image courtesy: Huld et al, 2008

A proper assessment of modules with different inclinations and orientations is essential to understand their characteristic behavior for different locations

This is not an optimisation, rather a sensitivity study

It aims to:

- quatify PV fluctuations on different temporal scales
- understand behavior of different module configurations in different sky conditions
- compare storage needs for different configurations and different geographic locations

Our model uses:

- 45(+15) module configurations for European countries
- a simple balancing model with 'no tranmission scenario'

Module configurations:

Primarily 45 configurations are analysed:

- five orientations (East, South-East, South, South-West, West)
- nine inclinations for each orientations

Orientations	Inclinations				
East	Opt±20°	Opt±15°	Opt±10°	Opt±5°	Optimal
South-East	Opt±20°	Opt±15°	Opt±10°	Opt±5°	Optimal
South	Opt±20°	Opt±15°	Opt±10°	Opt±5°	Optimal
South-West	Opt±20°	Opt±15°	Opt±10°	Opt±5°	Optimal
West	Opt±20°	Opt±15°	Opt±10°	Opt±5°	Optimal

Module configurations:

Additionally, 15 extreme configurations are analysed (only for Germany and Spain):

- five orientations (East, South-East, South, South-West, West)
- three inclinations for each orientations

Orientations	Inclinations		
East	Opt$\pm$30°	90°	0°
South-East	Opt$\pm$30°	90°	0°
South	Opt$\pm$30°	90°	0°
South-West	Opt$\pm$30°	90°	0°
West	Opt$\pm$30°	90°	0°
	Opt$\pm$30°	90°	0°

Terminologies:

$$Generation(t) = PV(t) + Onshorewind(t) + Offshorewind(t)$$

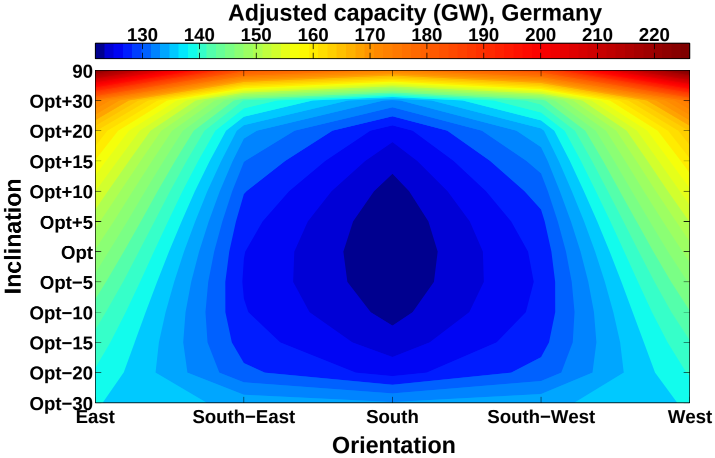
$$Installation\_factor(\alpha) = \frac{< Generation(t) >}{< Load(t) >}$$

For this simulation, the load is scaled such that the entire demand can be met by renewable generation only.

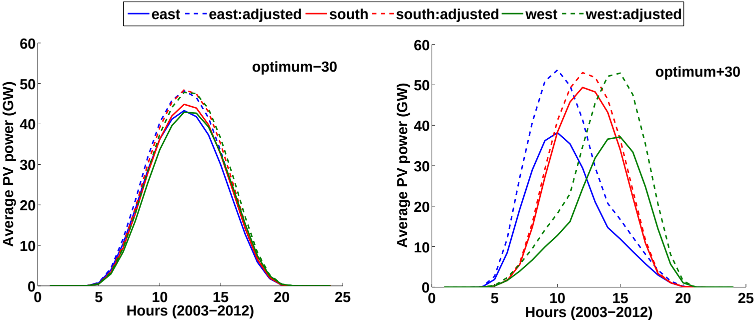
Adjusting capacity

- different configurations have different PV production potential
- to maintain uniformity, a levelised production is generated
- this is done by adjusting the capacity for different configurations

$$\boxed{Pinst_{conf} = Pinst_{RESTORE} \times \frac{< P_{RESTORE} >}{< P_{conf} >}}$$



For Germany, PV capacity from EREC scenario was originally 124.5 GW



Highly inclined modules require the most capacity adjustment, specially when oriented to east or west (example shown for Germany).

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Fluctuation analysis

Three different measures are adopted for fluctuation analysis:

- root-mean-square-error with respect to the original RESTORE-2050 timeseries **(rel-rmse)**
- **standard deviation** at different temporal resolutions
- **frequency distribution** of PV power from different configurations

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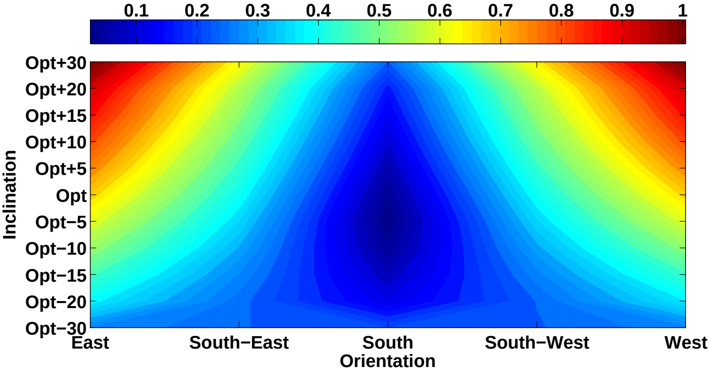
Relative RMSE



High rel-rmse values are noted for steeply inclined modules, specially when oriented towards east or towards west: example shown for Germany

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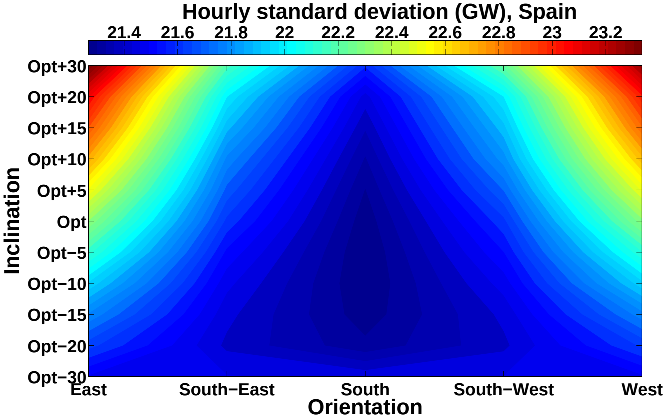
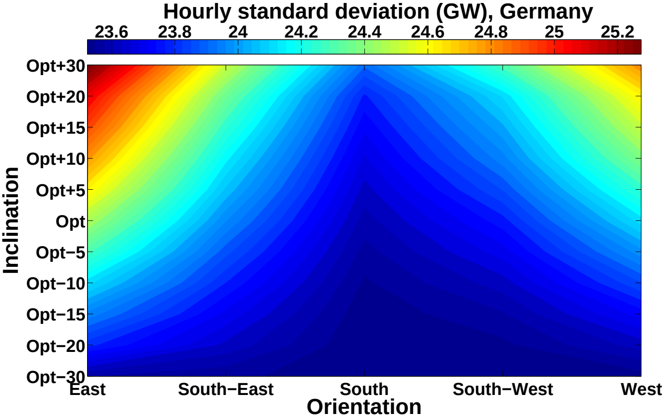
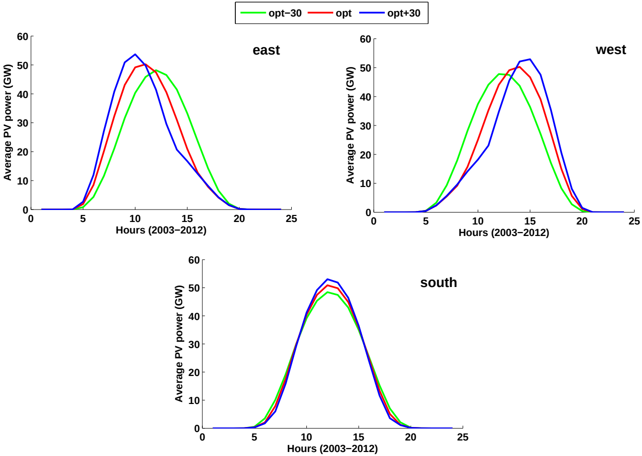


High standard deviation values are noted for steeply inclined modules, specially when oriented towards east or towards west

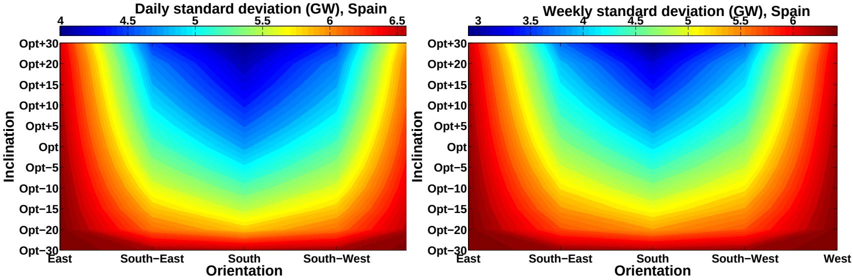


Asymmetry in hourly standard deviation with larger values for east oriented modules in Germany

Diurnal variation, Germany

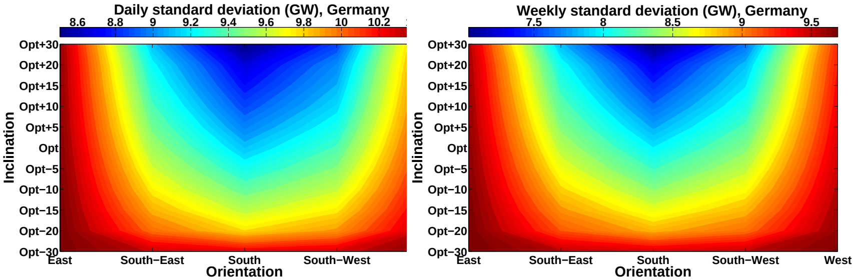


Daily & weekly deviations



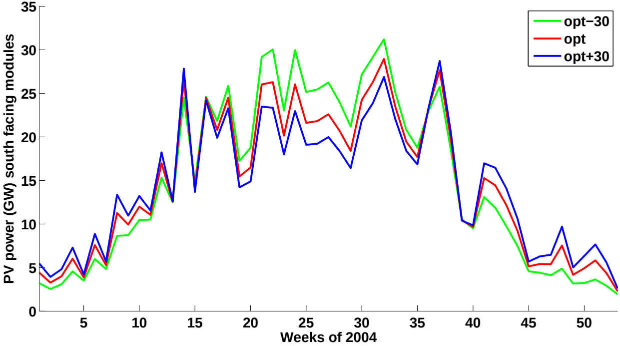
South-facing modules with high inclinations have low standard deviations on daily scale. For east/west-facing modules standard deviation remains substantially high for all inclinations.

Daily & weekly deviations

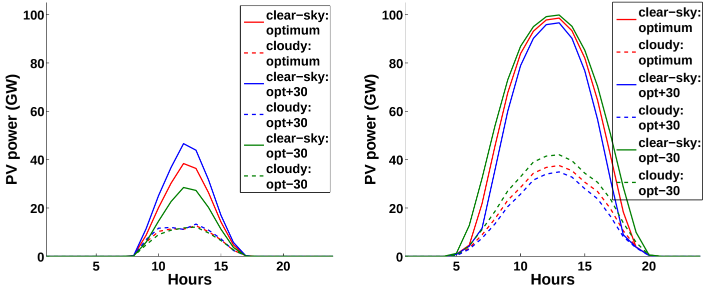


Asymmetry persists: by decreasing module inclination, east facing modules show faster increase in standard deviations compared to those facing west.

Weekly timeseries



On the annual course, low inclined modules show higher fluctuations than high inclined modules (example shown for Germany).



PV power production shown for example days in different seasons (left: January, right: July) for Germany

Three different measures are adopted for fluctuation analysis:

- root-mean-square-error with respect to the original RESTORE-2050 timeseries **(rel-rmse)**
- standard deviation at different temporal resolutions
- frequency distribution of PV power from different configurations

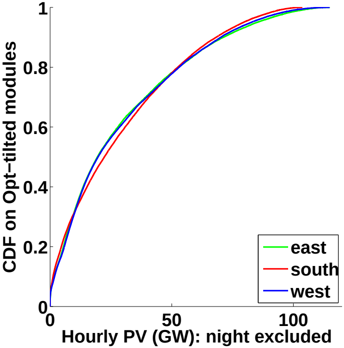
Frequency distributions

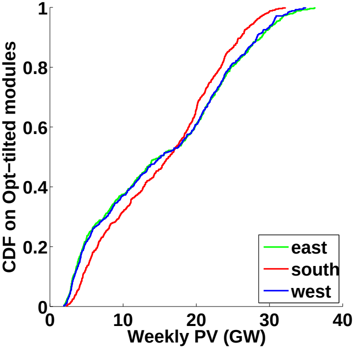
Frequency distributions are studied with cumulated distribution functions in different temporal resolutions (hourly and weekly shown for clarity).

- first we analyse optimally inclined modules in different orientations
- next we analyse south facing modules with different inclinations

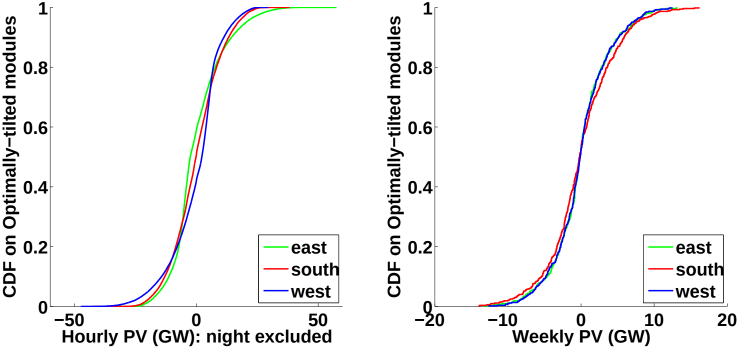
The distribution of all incremental timeseries for each is also analysed alongside.

Cumulated distributions



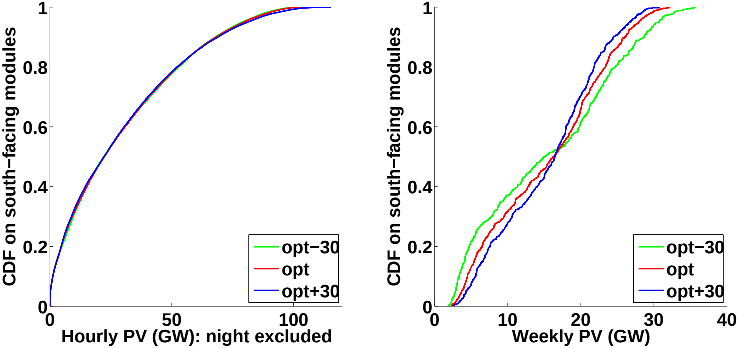


Cumulated distribution of hourly (left) and weekly (right) PV power for optimally inclined modules (example shown for Germany).



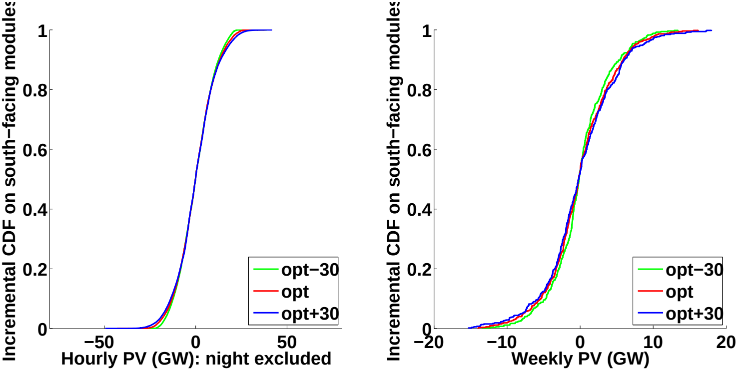
Incremental distribution of hourly (left) and weekly (right) PV power for optimally inclined modules (example shown for Germany).

Cumulated distributions



Cumulated distribution of hourly (left) and weekly (right) PV power for south-facing modules (example shown for Germany).

Incremental timeseries



Incremental distribution of hourly (left) and weekly (right) PV power for south-facing modules (example shown for Germany).

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Storage related terminologies:

$$mismatch(t) = Generation(t) - \alpha \times Load(t)$$

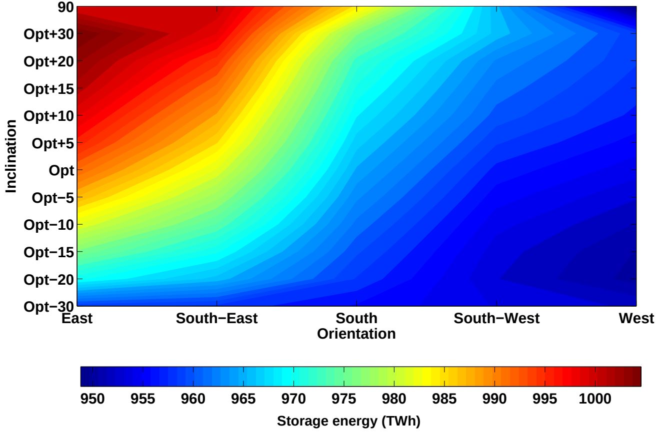
$$residual\_load(t) = (mismatch(t) < 0)$$

$$storage\_energy = \int_t residual\_load(t)dt$$

$$relative\_storage\_energy = \frac{storage\_energy}{\int_t (\alpha \times Load(t))dt}$$

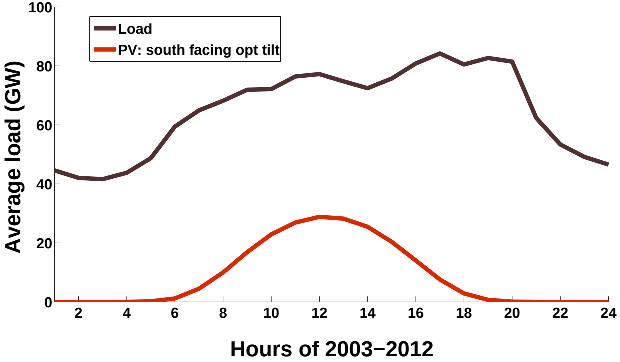
For simplification, no storage loss is calculated for now!

Storage energy



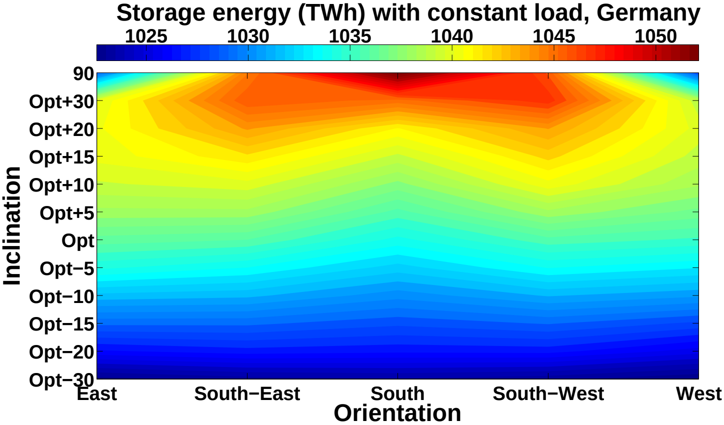
Storage energy (hourly) with strong east-west asymmetry for Germany

Average load



Annual average of hourly load and PV power from south-facing optimally tilted modules for Germany

Storage energy



The asymmetry vanishes but the magnitude of storage energy (hourly) increases.

Storage energy

	All years		2004		2007	
Module inclinations	Total storage (TWh)	Rel. to total load (%)	Total storage (TWh)	Rel. to total load (%)	Total storage (TWh)	Rel. to total load (%)
$Opt - 30°$	956.44	**24.5**	98.90	**25.2**	89.10	**22.8**
Opt	965.34	**24.7**	100.07	**25.5**	90.04	**23.0**
$Opt + 30°$	976.91	**25.0**	101.28	**25.8**	91.04	**23.3**

Hourly storage energy for south facing modules in Germany: small difference between different configurations, but interannual differences can be comparatively large

Storage related terminologies:

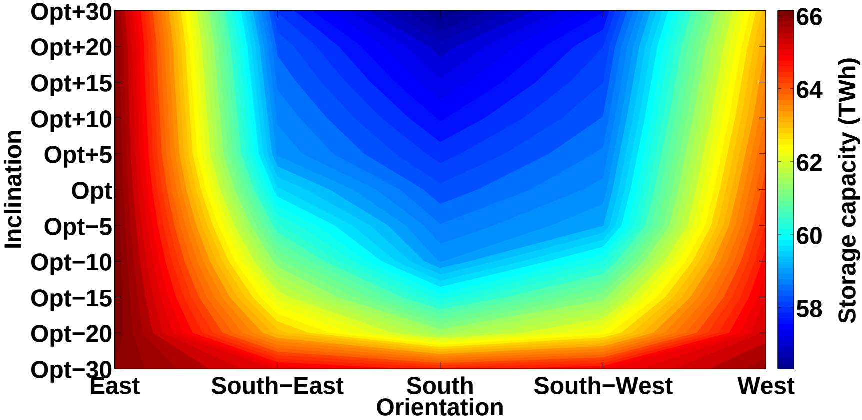
$$storage\_filling = \int_t mismatch(t)dt$$

$$storage\_capacity = max(storage\_filling) - min(storage\_filling)$$

$$relative\_storage\_capacity = \frac{storage\_capacity}{< \alpha \times Load(t) >}$$

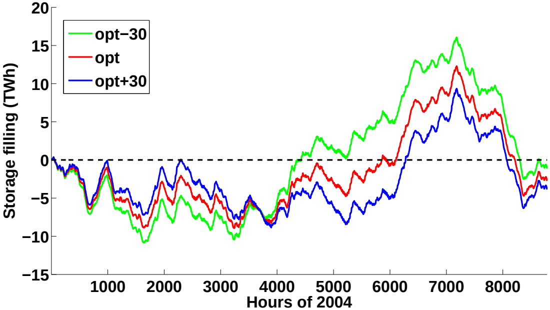
For simplification, no storage loss is calculated for now!

Storage capacity



For Germany: high inclined south-facing modules are prefered

Storage filling



Hourly storage filling for Germany, 2004 for south facing modules with different inclinations (opt-30°,opt,opt+30°).

Storage capacity

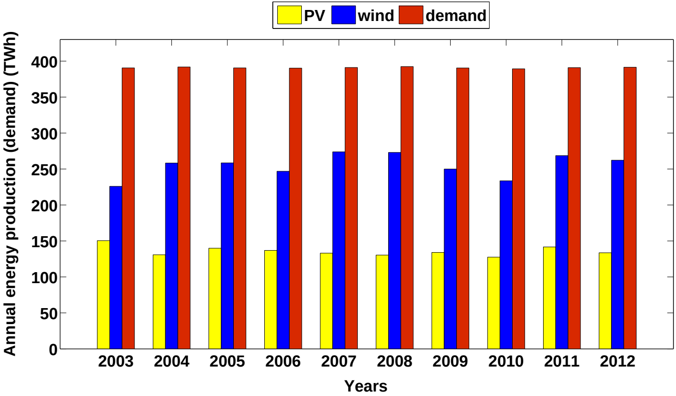
	All years		2004		2007	
Module inclinations	Total capacity (TWh)	Rel. to average load (h)	Total capacity (TWh)	Rel. to average load (h)	Total capacity (TWh)	Rel. to average load (h)
$Opt - 30°$	**64.66**	1450.4	**26.91**	603.21	**36.85**	825.45
Opt	**58.35**	1308.9	**21.24**	476.25	**33.16**	742.70
$Opt + 30°$	**56.33**	1263.6	**18.19**	407.85	**30.03**	672.62

Hourly storage capacity for south facing modules in Germany:
Relative changes for different configurations still small
but interannual differences are substantially larger

Storage filling

Weekly timeseries for south-facing optimally inclined modules in Germany

Annual energy



Interannual variation of energy production from PV and wind (onshore & offshore) and energy demand for Germany

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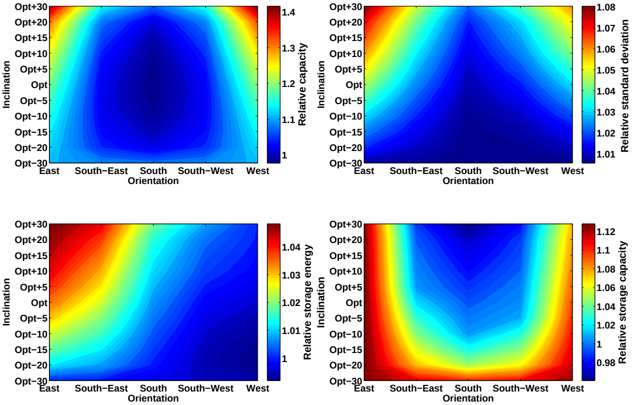
We summarise the presentation with a quick look back on:

- capacity adjustment
- calculating fluctuations
- calculating storage energy
- calculating storage requirement

for different module configurations



Overview of behavior from different configurations for Germany relative to original RESTORE-2050 timeseries with ISI configuration

Summary

Location of optimum for different categories in Germany:

- capacity adjustment: optimally tilted south-facing modules
- fluctuations: low inclined south or south-west facing modules
- storage energy: low inclined west facing modules
- storage requirement: south facing highly inclined modules

Frequency distribution: highly inclined modules have less fluctuations but their associated changes from one time step to the next could be high.

Outlook

- Extend the analysis to other European countries
- Include storage loss in calculation
- Analyse the fluctuations from east-west mixed timeseries at different temporal resolutions
- Include hydro power in the model
- Modify the existing code to allow power transmission across Europe

Thank You for your Attention!

Questions?

Storage energy

Module inclinations	All years		2004		20007	
	Total (TWh)	Relative	Total (TWh)	Relative	Total (TWh)	Relative
East	992.24	0.254	101.61	0.259	92.32	0.236
South	965.34	0.247	100.07	0.255	90.04	0.230
West	954.82	0.244	98.88	0.252	89.26	0.228

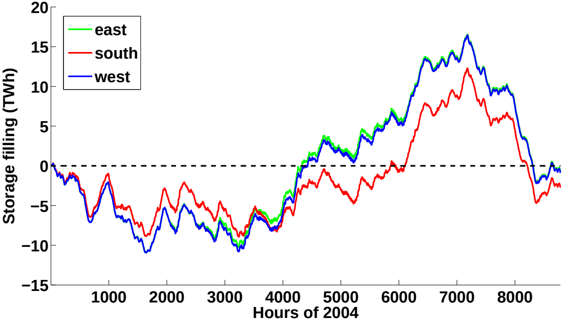
Examples of storage energy shown for optimally inclined modules in Germany

Storage energy (TWh)

Temporal resolutions	**All years**	**2004**	**2007**
Hourly	965.34	100.07	90.04
Daily	625.67	69.04	56.24
Weekly	385.04	42.74	34.26

Storage energy on different temporal resolutions for south facing optimally tilted modules in Germany.

Storage filling



Hourly storage filling for Germany, 2004 for optimally inclined modules with different orientations (east, south, west)

Storage capacity

Module inclinations	All years		2004		2007	
	Total (TWh)	Relative (h)	Total (TWh)	Relative (h)	Total (TWh)	Relative (h)
East	66.30	1487.2	27.49	616.25	37.32	836.06
South	58.35	1308.9	21.24	476.25	33.16	742.70
West	64.32	1442.8	27.40	614.27	36.78	823.94

Examples of storage capacity shown for optimally inclined modules in Germany