What can transmission do for a renewable Europe?

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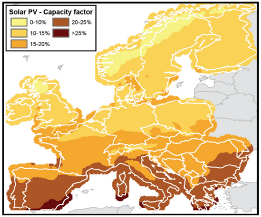
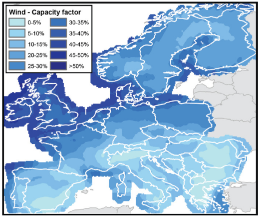
Weather-driven electricity generation

Generation from weather data

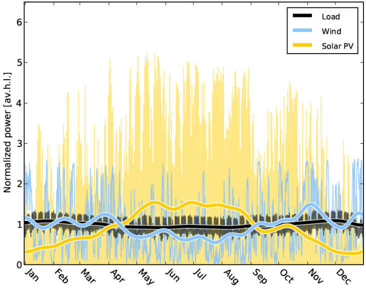




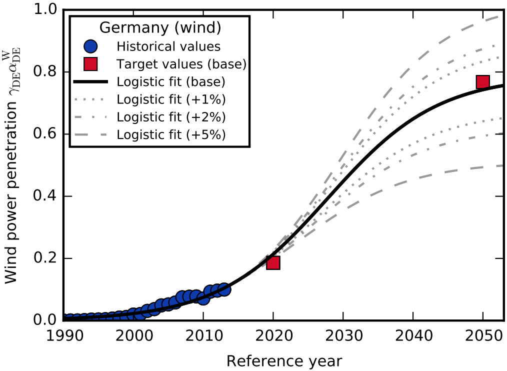
Mismatch to load

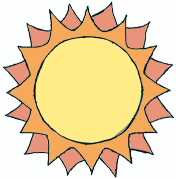
$$\Delta_n(t) = \gamma_n \left(\alpha_n^{\mathrm{W}} W_n(t) + (1 - \alpha_n^{\mathrm{W}}) S_n(t) \right) \langle L_n \rangle - L_n(t)$$

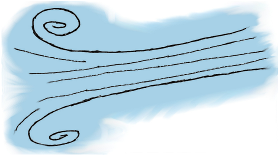
Δ_n – mismatch at node n, L_n – load, W_n – norm. wind generation, S_n – norm. solar PV generation, γ_n – gross VRES share, α_n^{W} – relative wind share



Logistic fit

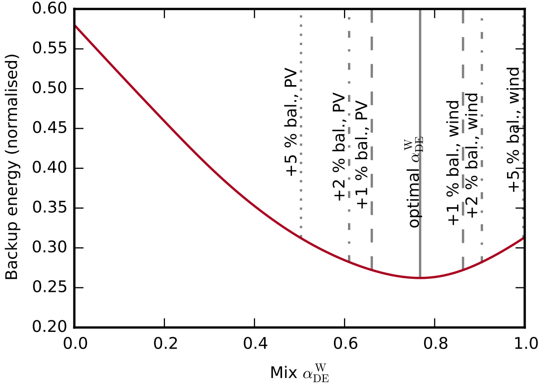






Logistic growth function: $f(y; y_0, a, b, m) = \frac{a \cdot b \cdot e^{m(y-y_0)}}{a(e^{m(y-y_0)}-1)+b}$

End-point mixes



DC power flow

Given Δ_n for all nodes n, solve for F:

$\Delta_n - (KF)_n = 0$	–	cover deficits with surplusses
$\min \sum_l F_l^2$	–	minimize transmission dissipation

Δ_n – power surplus/deficit at node n,
F_l – power flow along link l,
K – incidence matrix, encodes network topology,
$(KF)_n$ – net flow out of node n

Generalisation

DC power flow only works for

- $\sum_n \Delta_n = 0$ – energy conservation
- Unconstrained flows

$\Rightarrow$ Generalisation:

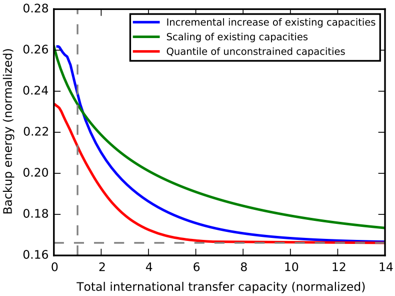
$\min \sum_n (\Delta_n - (KF)_n)_- = \min \sum_n B_n$	– minimize residual deficit
$\min \sum_l F_l^2$	– minimize dissipation

- Back-up power to cover deficits if needed
- Shed surplusses if necessary
- Constraints on the transmission line capacities
  $h_{-l} \leq F_l \leq h_l$

Benefit of transmission

Two extreme cases:

- No transmission – C_{zero}
  $\Rightarrow$ high total back-up energy $B_{\text{tot}}(C_{\text{zero}})$
- Unconstrained transmission – $C_{\text{unconstrained}}$
  $\Rightarrow$ low total back-up energy $B_{\text{tot}}(C_{\text{unconstrained}})$



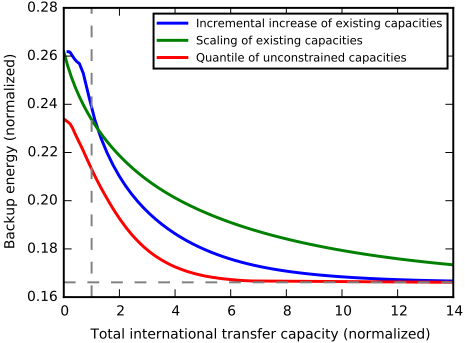
Benefit of transmission of a general transmission layout C_{CL}:

$$\beta_{\text{CL}} = \frac{B_{\text{tot}}(C_{\text{zero}}) - B_{\text{tot}}(C_{\text{CL}})}{B_{\text{tot}}(C_{\text{zero}}) - B_{\text{tot}}(C_{\text{unconstrained}})}$$

Resonable compromise:
90 % benefit of transmission capacities

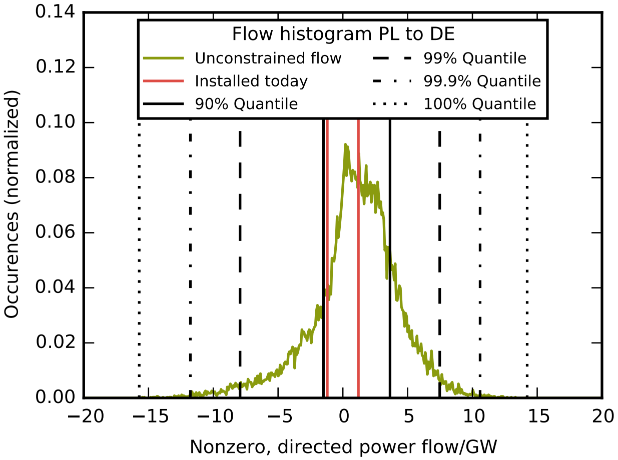
Choice of interpolation

Which links should be reinforced first?

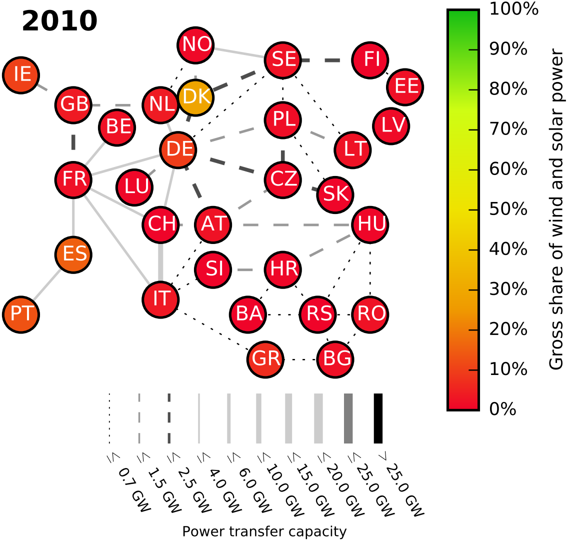


- Multiples of today's capacities
- Different quantiles of unconstrained flow

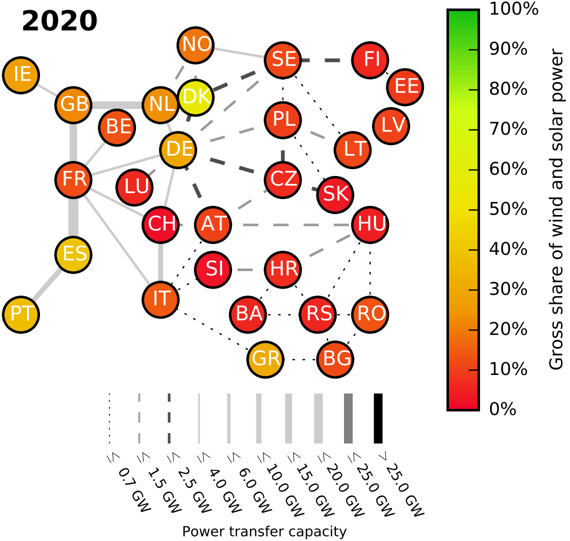
Quantile line capacities



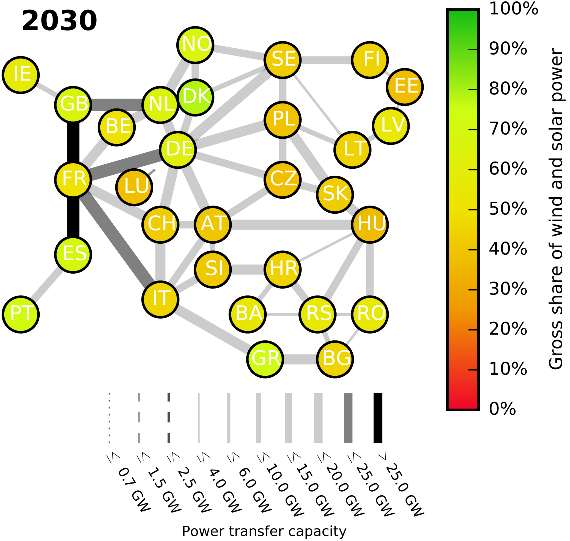
Network evolution



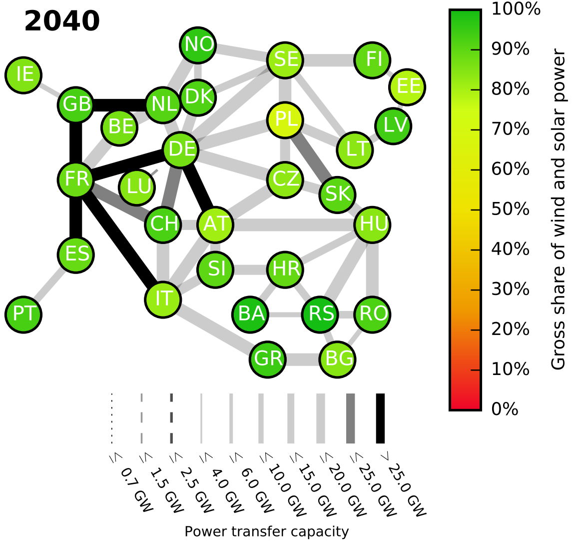
Network evolution



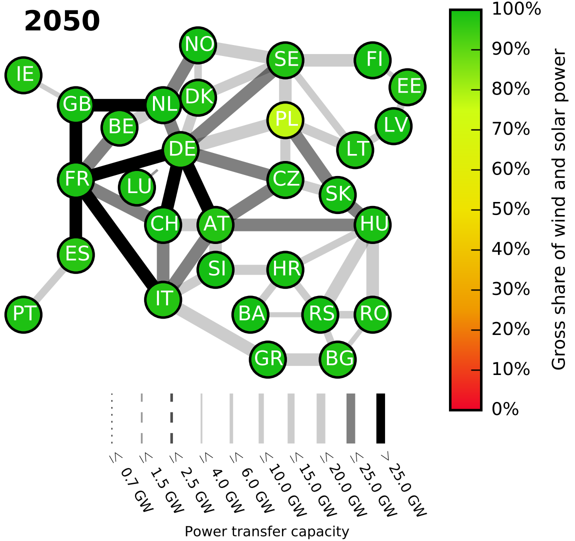
Network evolution



Network evolution

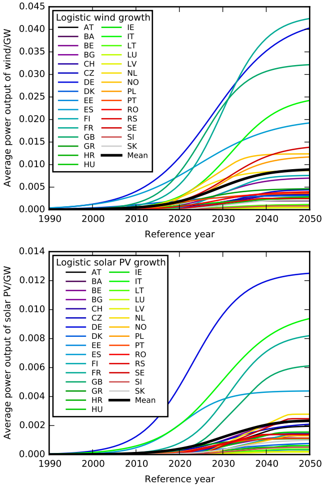


Network evolution

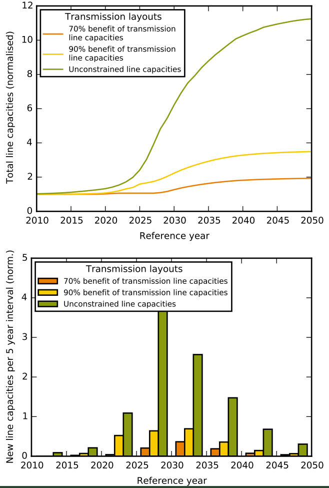


Investment per five year interval

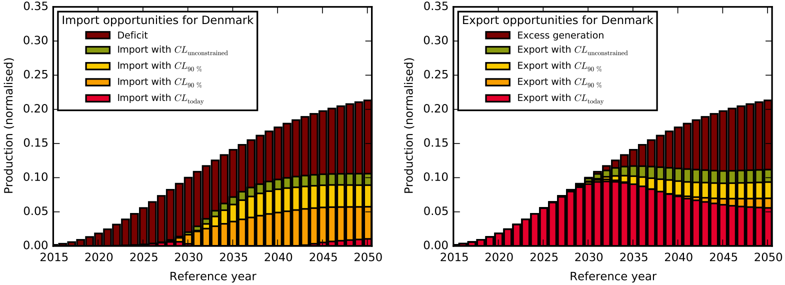
Logistic growth of wind (a) and solar PV (b) power



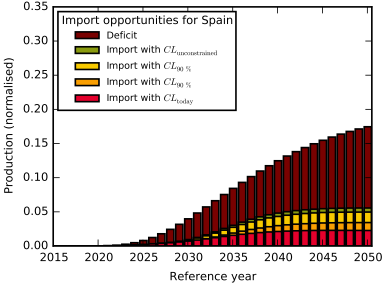
Growth in 90% benefit line capacities (a) and incremental investment per five-years (b)

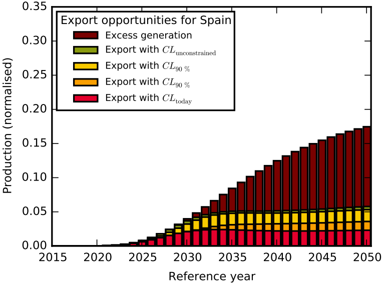


Denmark

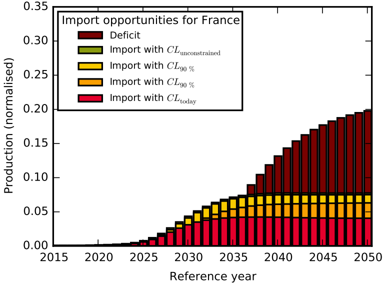

Import opportunities for Denmark
Deficit
Import with $CL_{\text{unconstrained}}$
Import with $CL_{90\ \%}$
Import with $CL_{90\ \%}$
Import with CL_{today}
Production (normalised)
Reference year
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
2015
2020
2025
2030
2035
2040
2045
2050
Export opportunities for Denmark
Excess generation
Export with $CL_{\text{unconstrained}}$
Export with $CL_{90\ \%}$
Export with $CL_{90\ \%}$
Export with CL_{today}
Production (normalised)
Reference year

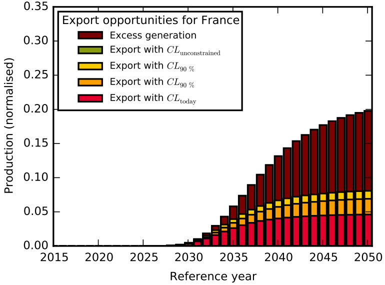
Spain


Import opportunities for Spain
Deficit
Import with $CL_{\mathrm{unconstrained}}$
Import with $CL_{90\ \%}$
Import with $CL_{90\ \%}$
Import with CL_{today}
Production (normalised)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
2015
2020
2025
2030
2035
2040
2045
2050
Reference year

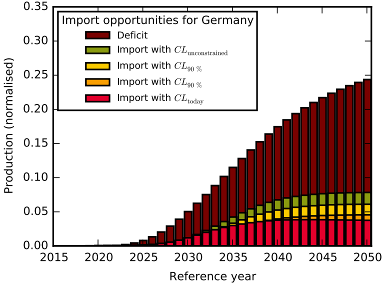

Export opportunities for Spain
Excess generation
Export with $CL_{\mathrm{unconstrained}}$
Export with $CL_{90\ \%}$
Export with $CL_{90\ \%}$
Export with CL_{today}
Production (normalised)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
2015
2020
2025
2030
2035
2040
2045
2050
Reference year

France


Import opportunities for France
Deficit
Import with $CL_{\text{unconstrained}}$
Import with $CL_{90\ \%}$
Import with $CL_{90\ \%}$
Import with CL_{today}
Production (normalised)
Reference year
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
2015
2020
2025
2030
2035
2040
2045
2050


Export opportunities for France
Excess generation
Export with $CL_{\text{unconstrained}}$
Export with $CL_{90\ \%}$
Export with $CL_{90\ \%}$
Export with CL_{today}
Production (normalised)
Reference year
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
2015
2020
2025
2030
2035
2040
2045
2050

Germany


Import opportunities for Germany
Deficit
Import with $CL_{\text{unconstrained}}$
Import with $CL_{90\ \%}$
Import with $CL_{90\ \%}$
Import with CL_{today}
Production (normalised)
0.00
0.05
0.10
0.15
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0.25
0.30
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2015
2020
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2035
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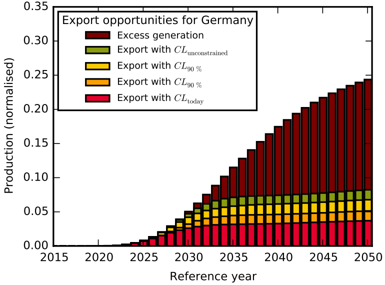
2045
2050
Reference year


Export opportunities for Germany
Excess generation
Export with $CL_{\text{unconstrained}}$
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Production (normalised)
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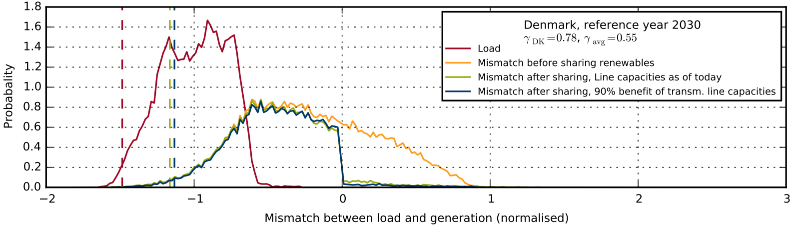
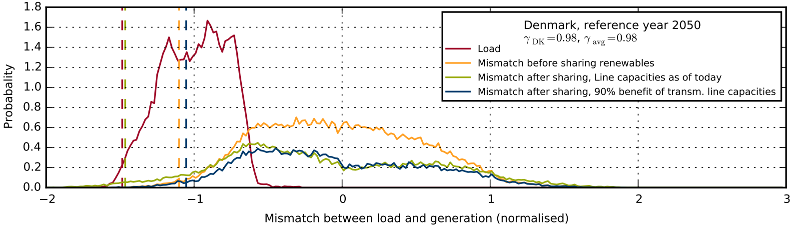
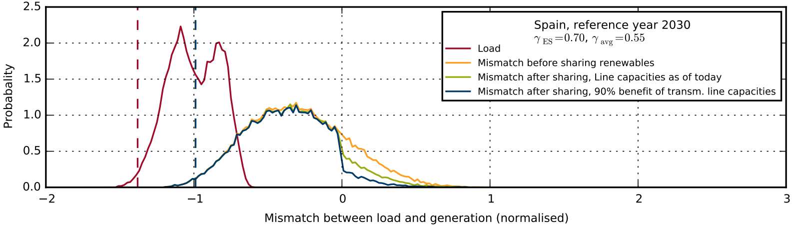
Reference year

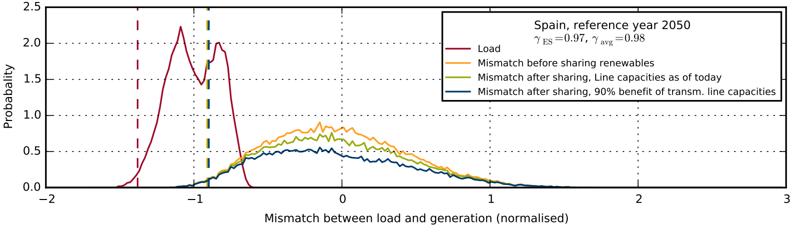
Denmark


Denmark, reference year 2030
$\gamma_{\mathrm{DK}} = 0.78$, $\gamma_{\mathrm{avg}} = 0.55$
Load
Mismatch before sharing renewables
Mismatch after sharing, Line capacities as of today
Mismatch after sharing, 90% benefit of transm. line capacities
Probabality
Mismatch between load and generation (normalised)

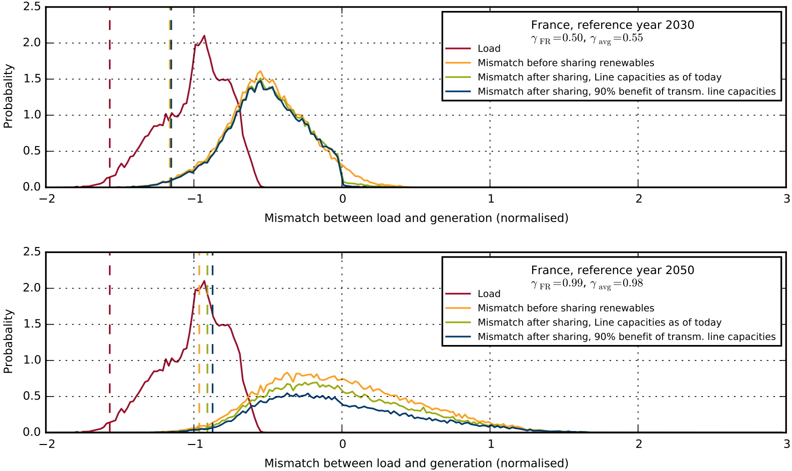

Denmark, reference year 2050
$\gamma_{\mathrm{DK}} = 0.98$, $\gamma_{\mathrm{avg}} = 0.98$
Load
Mismatch before sharing renewables
Mismatch after sharing, Line capacities as of today
Mismatch after sharing, 90% benefit of transm. line capacities
Probabality
Mismatch between load and generation (normalised)

Spain

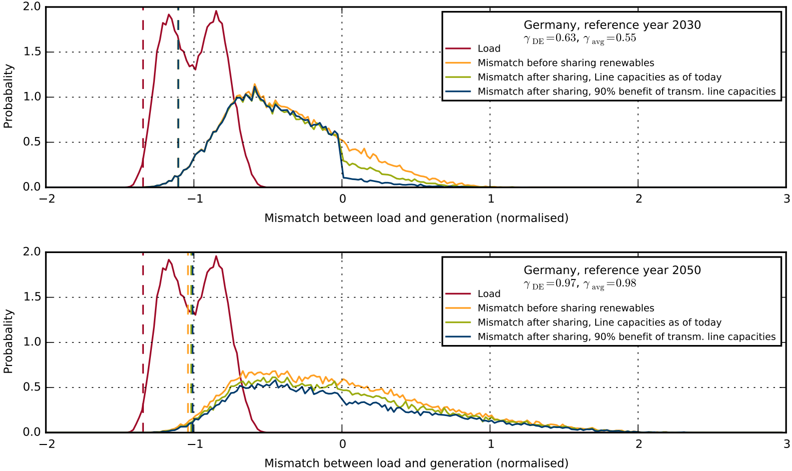

Spain, reference year 2030
$\gamma_{ES}=0.70$, $\gamma_{avg}=0.55$
Load
Mismatch before sharing renewables
Mismatch after sharing, Line capacities as of today
Mismatch after sharing, 90% benefit of transm. line capacities
Probabality
Mismatch between load and generation (normalised)


Spain, reference year 2050
$\gamma_{ES}=0.97$, $\gamma_{avg}=0.98$
Load
Mismatch before sharing renewables
Mismatch after sharing, Line capacities as of today
Mismatch after sharing, 90% benefit of transm. line capacities
Probabality
Mismatch between load and generation (normalised)

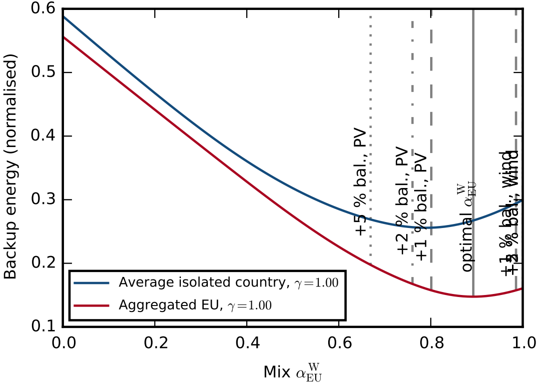
France


France, reference year 2030
$\gamma_{FR}=0.50$, $\gamma_{avg}=0.55$
Load
Mismatch before sharing renewables
Mismatch after sharing, Line capacities as of today
Mismatch after sharing, 90% benefit of transm. line capacities
Probabality
Mismatch between load and generation (normalised)
France, reference year 2050
$\gamma_{FR}=0.99$, $\gamma_{avg}=0.98$
Load
Mismatch before sharing renewables
Mismatch after sharing, Line capacities as of today
Mismatch after sharing, 90% benefit of transm. line capacities
Probabality
Mismatch between load and generation (normalised)

Germany

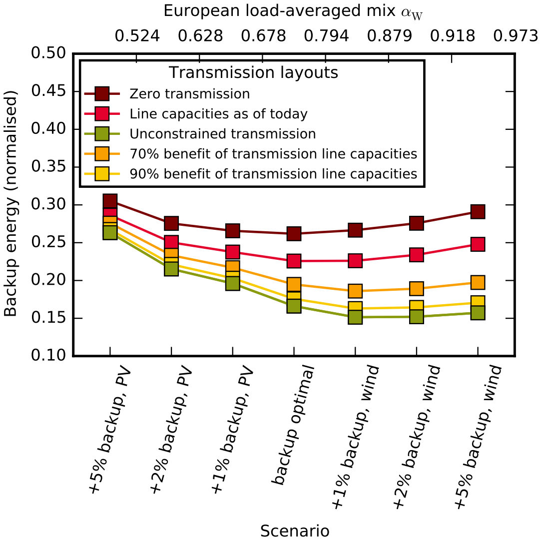

Germany, reference year 2030
$\gamma_{\rm DE}=0.63$, $\gamma_{\rm avg}=0.55$
Load
Mismatch before sharing renewables
Mismatch after sharing, Line capacities as of today
Mismatch after sharing, 90% benefit of transm. line capacities
Probabality
Mismatch between load and generation (normalised)
Germany, reference year 2050
$\gamma_{\rm DE}=0.97$, $\gamma_{\rm avg}=0.98$
Load
Mismatch before sharing renewables
Mismatch after sharing, Line capacities as of today
Mismatch after sharing, 90% benefit of transm. line capacities
Probabality
Mismatch between load and generation (normalised)

End-point mixes



$$\alpha^{W}_{\text{opt, EU agg.}} = 0.894, \quad \alpha^{W}_{\text{opt, EU avg.}} = 0.794$$

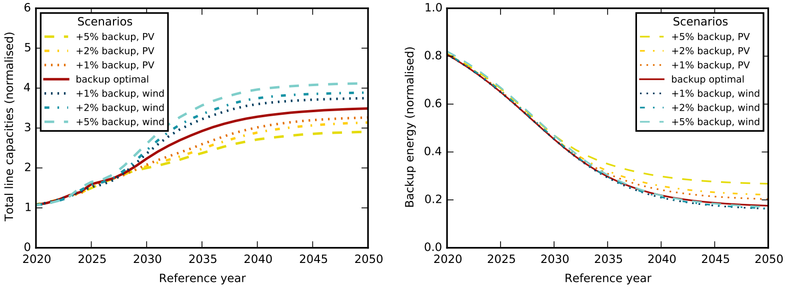
Shift of optimal mix



Wind resources decorrelate at distances around 500–1000 km

J. Widén. Correlations between large-scale solar and wind power in a future scenario for Sweden. IEEE Transactions on 184, 2011.

Linecaps/Backup tradeoff



Conclusions

Model ingredients:

- Weather-based modelling
- Logistic growth of renewable installations
- DC power flow

Results:

- Quantile line capacities useful approach
- Quadrupling today's line capacities yields 90% of potential benefit
- Transmission reduces backup energy by up to 40% BUT does not provide last-resort secure capacity
- Especially during critical times, backup power is not much reduced

Further reading and references: Becker, S., Rodríguez, R.A., Andresen, G.B., Schramm, S., and Greiner, M.: *Transmission grid extensions during the build-up of a fully renewable pan-European electricity supply*, Energy **64**, p. 404-418 (2014). Online at http://dx.doi.org/10.1016/j.energy.2013.10.010; preprint available at http://arxiv.org/abs/1307.1723.