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Market-based valuation of transmission network expansion. A heuristic application in GB

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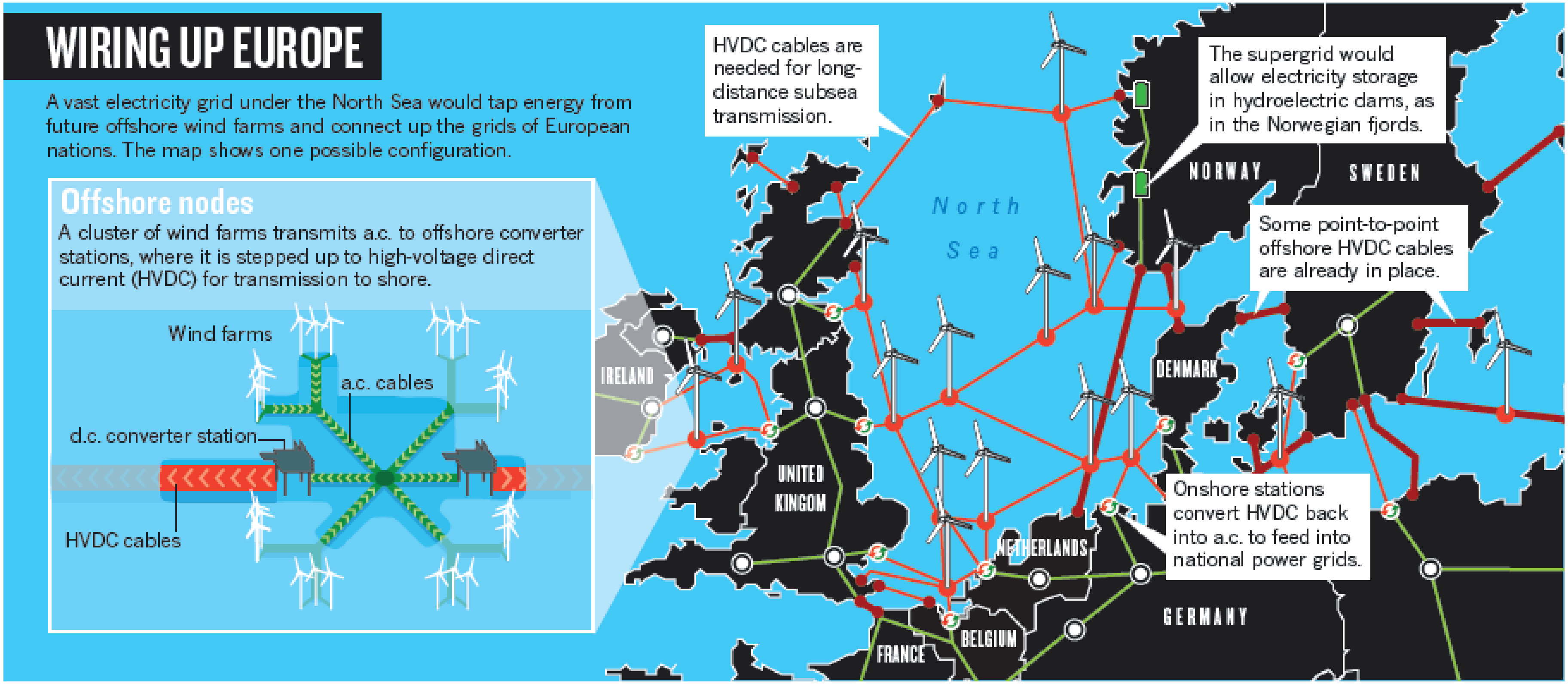


WIRING UP EUROPE

A vast electricity grid under the North Sea would tap energy from future offshore wind farms and connect up the grids of European nations. The map shows one possible configuration.

Offshore nodes

A cluster of wind farms transmits a.c. to offshore converter stations, where it is stepped up to high-voltage direct current (HVDC) for transmission to shore.

HVDC cables are needed for long-distance subsea transmission.

The supergrid would allow electricity storage in hydroelectric dams, as in the Norwegian fjords.

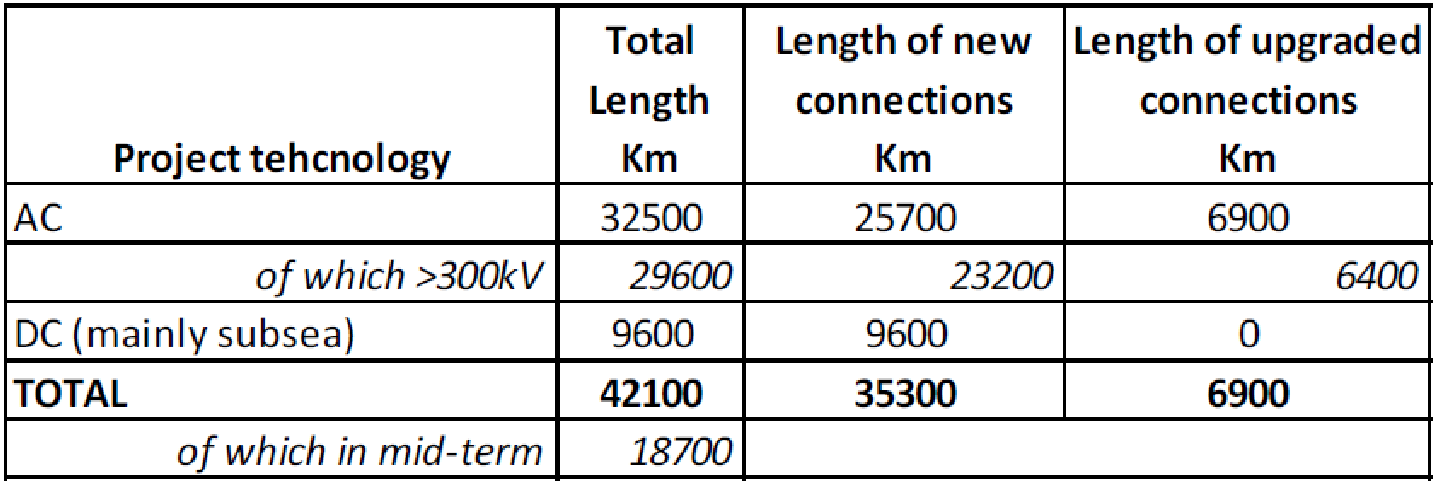
Some point-to-point offshore HVDC cables are already in place.

Onshore stations convert HVDC back into a.c. to feed into national power grids.

Macilwain C. (2010): “Supergrid”. Nature , Vol. 468, 2 December, pp. 624-625.

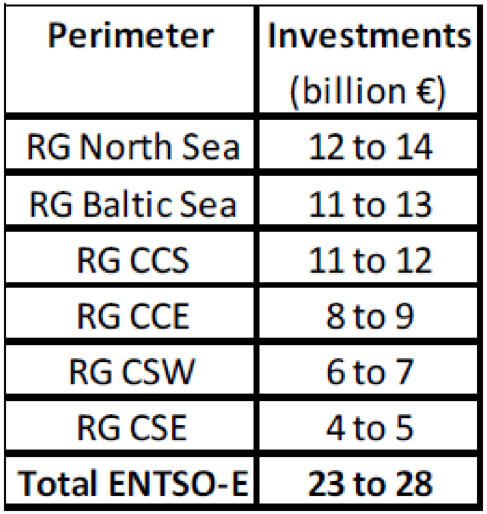
“A report published in July by the EU-funded research project OffshoreGrid, based in Brussels, envisages, for example, that €32 billion will be invested in offshore interconnectors in northern Europe by 2020”.

TABLE 1 LENGTH OF NEW AND REFURBISHED POWER LINES UNTIL 2020 (PROJECTS OF EUROPEAN SIGNIFICANCE)



Project tehcnology	Total Length Km	Length of new connections Km	Length of upgraded connections Km
AC	32500	25700	6900
of which >300kV	*29600*	*23200*	*6400*
DC (mainly subsea)	9600	9600	0
TOTAL	**42100**	**35300**	**6900**
of which in mid-term	*18700*		

TABLE 2 INVESTMENT COSTS OF TRANSMISSION PROJECTS OF EUROPEAN SIGNIFICANCE TO BE COMPLETED WITHIN THE PERIOD 2010-2014



Perimeter	Investments (billion €)
RG North Sea	12 to 14
RG Baltic Sea	11 to 13
RG CCS	11 to 12
RG CCE	8 to 9
RG CSW	6 to 7
RG CSE	4 to 5
Total ENTSO-E	**23 to 28**

WHAT ARE THE EXPECTED BENEFITS?

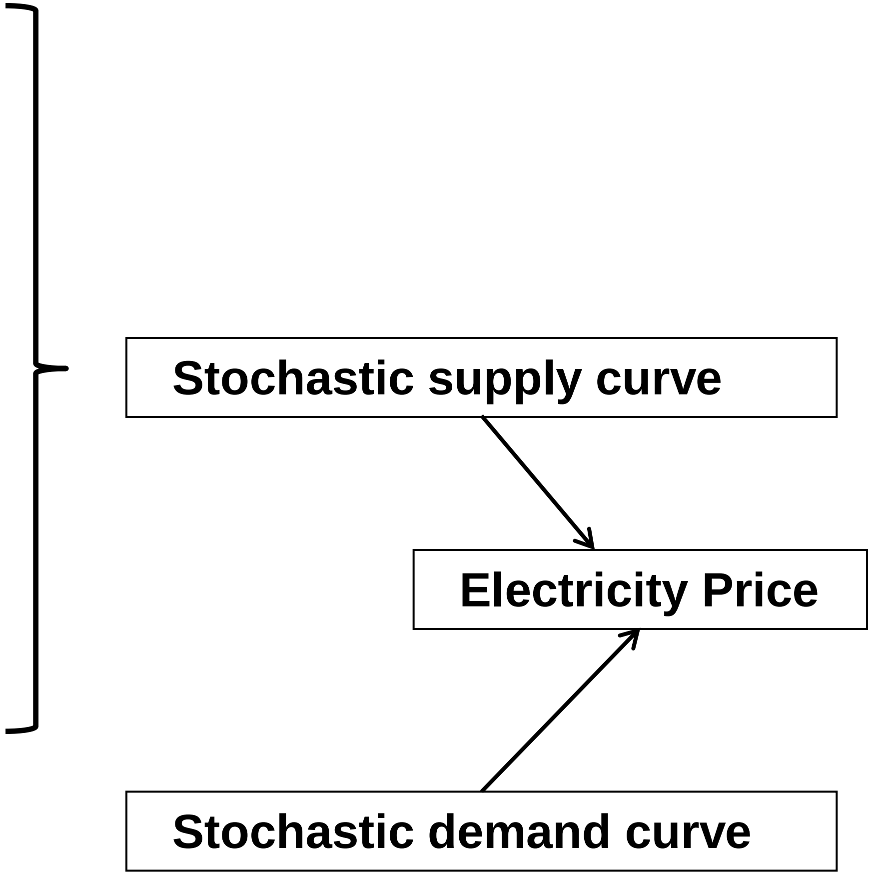
ENTSOe: (2010): TEN-YEAR NETWORK DEVELOPMENT PLAN 2010-2020

Background

- Transmission and distribution infrastructures: severe problem of aging.
- Challenges (and opportunities) ahead: increasing demand, security of supply, climate change, integration of renewables.
- **Focus**: whether to invest or not in a new transmission line;
    - two-node network, with generators and loads at each node, under carbon restrictions
    - coal, natural gas, nuclear, wind, and hydro power plants
    - natural gas stations are the marginal units
- **Sources of risk**:
    - Physical: load, power plant contingency, transmission line contingency
    - Economic: coal price, natural gas price, carbon price
- **Methodology:** Optimal dispatch, Monte Carlo simulation, risk-neutral valuation
- **Example:** proposed Western HVDC subsea link between Scotland and England.
- **Output**: whole distribution of effects for key factors over the project’s whole useful lifetime.

Model features

- Stochastic price models
  - Coal
  - Natural gas
  - CO2 emission allowance
- Stochastic contingencies
  - Power plants
  - Transmission lines
  - Renewable generation
- Operational characteristics:
  - Power plant efficiency
  - Transmission losses
- Financial margins
- Stochastic (correlated) demands



Stochastic supply curve

Electricity Price

Stochastic demand curve

Physical and economic environment

- Nodal loads (i = 1, 2): $d^i = D^i + P^i$
- Power generation:

$$S_c^i = \left\{\begin{matrix} 0, \text{'off' state with probability } 1 - \Lambda_c dt \\ 1, \text{'on' state with probability } \Lambda_c dt \end{matrix}\right\},$$

$$S_g^i = \left\{\begin{matrix} 0, \text{'off' state with probability } 1 - \Lambda_g dt \\ 1, \text{'on' state with probability } \Lambda_g dt \end{matrix}\right\},$$

$$S_n^i = \left\{\begin{matrix} 0, \text{'off' state with probability } 1 - \Lambda_n dt \\ 1, \text{'on' state with probability } \Lambda_n dt \end{matrix}\right\}.$$

- Power transmission:

$$L^{ij} = \left\{\begin{matrix} 0, \text{'off' state with probability } 1 - \Lambda_L dt \\ 1, \text{'on' state with probability } \Lambda_L dt \end{matrix}\right\}.$$

- Demand-side costs: $\left(d^1 + d^2 - s^1 - s^2\right) \times VOLL$
- Supply-side costs:

$$c(x_1, x_2) = x_c\left(M_m + \frac{C + 0.34056A}{H_C}\right) +$$

$$+ x_g\left(M_m + \frac{G + 0.20196A}{H_G}\right) + x_p 1.1\left(M_m + \frac{0.20196A}{H_G}\right).$$

Economic dispatch

$$\min_{\{x_c^1, x_g^1, x_p^1, x_c^2, x_g^2, x_p^2, s^1, s^2\}} c(x_c^1, x_g^1, x_p^1, x_c^2, x_g^2, x_p^2) + \left(d^1 + d^2 - s^1 - s^2\right) \times VOLL$$

$$0 \leq x_f^1 \leq a_f^1 \overline{x}_f^1; 0 \leq x_f^2 \leq a_f^2 \overline{x}_f^2; f = \{c, g, n, w, h, p\};$$

$$0 \leq s^1 \leq d^1; 0 \leq s^2 \leq d^2;$$

$$\sum_f x_f^1 + \sum_f x_f^2 = s^1 + s^2 + m^{12};$$

$$\sum_f x_f^1 - s^1 \leq b^{12} l^{12}; \sum_f x_f^2 - s^2 \leq b^{12} l^{12};$$

$$dD = a(D,t)dt + b(D,t)dV; \; D = \{D^1, D^2\};$$

$$dR = a(R,t)dt + b(R,t)dY; \; R = \{W, H, P\};$$

$$dX = a(X,t)dt + b(X,t)dZ; \; X = \{C, G, A\}$$

Stochastic Optimal Control (Monte Carlo simulation + optimization)

- 750 simulations.
- Each simulation: 1,200 steps.
- 60 steps per year → 20 years.
- 900,000 optimizations with:
  - Minimization:

    Total Cost = Generation cost + Unserved load cost (VOLL)
  - Linear restrictions:

    Generation limits

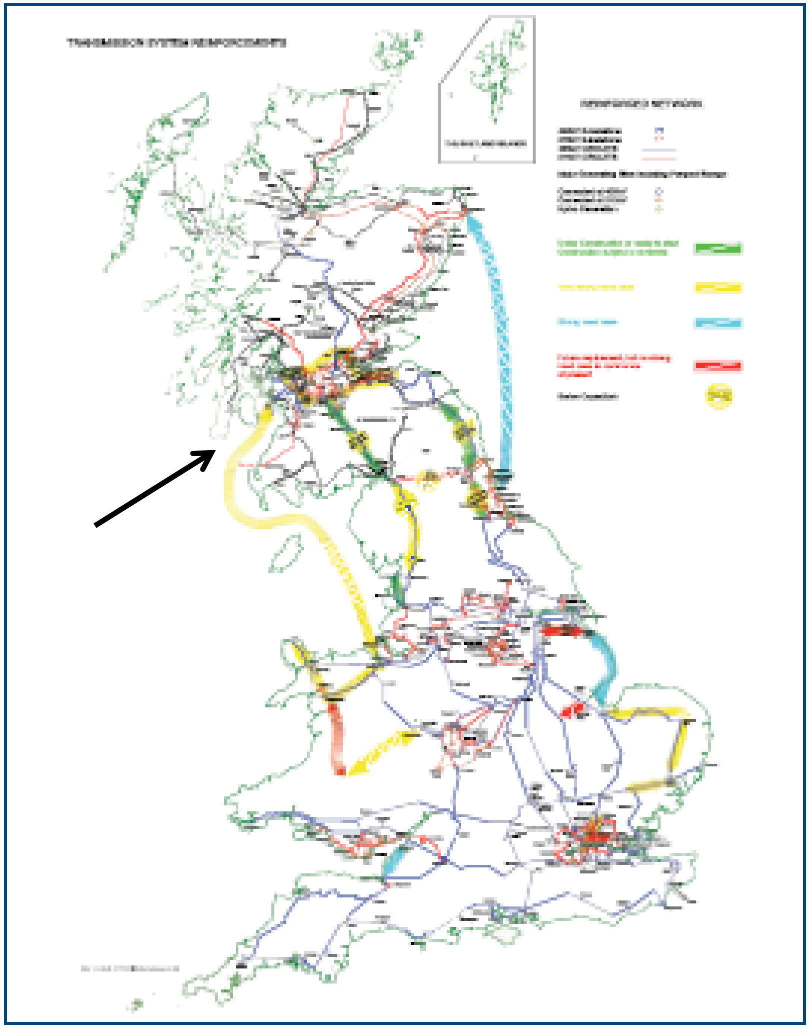
    Power supplied (i) ≤ Power demanded (i)

    Total generation = Power served + Losses

    Line flow limits of the network
  - Non-linear restrictions
- Output variables: power generated, load served. Hence: total cost, CO2 emissions, emissions costs, generation costs, unserved load, losses.
- Comparison between scenarios L1 and L1+L2: benefits of expansion.

A heuristic application in GB

Electricity Networks Strategy Group (2009): “Our electricity transmission network: A vision for 2020”.



(Stylized) Case study: Interconnector between Scotland and England/Wales.

Existing circuit: A 2.2 GW link, already operating at its maximum capability.

Potential upgrade: The Western subsea High Voltage Direct Current (HVDC) Link, a 1.8 GW HVDC link between Hunterston and Deeside.

Total cost: £760M.
What are the expected benefits?

- Generation capacity:

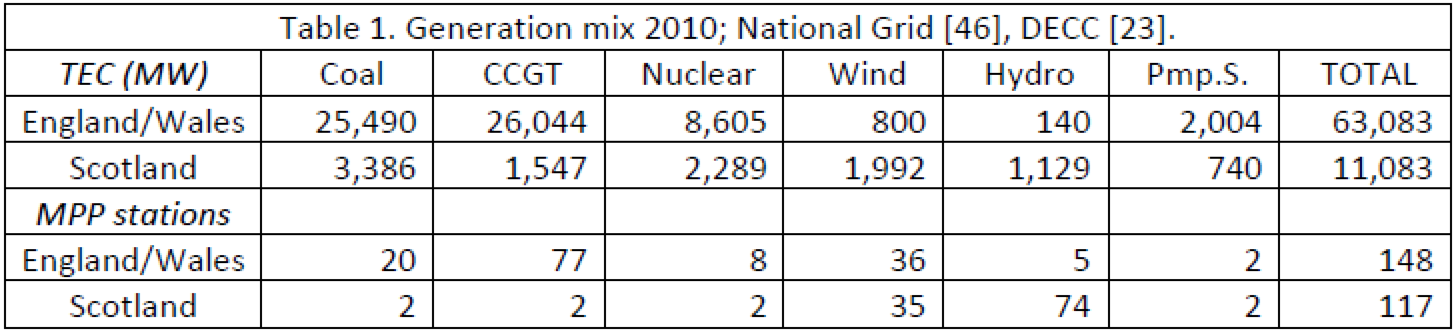


Table 1. Generation mix 2010; National Grid [46], DECC [23].

TEC (MW)	Coal	CCGT	Nuclear	Wind	Hydro	Pmp.S.	TOTAL
England/Wales	25,490	26,044	8,605	800	140	2,004	63,083
Scotland	3,386	1,547	2,289	1,992	1,129	740	11,083
MPP stations							
England/Wales	20	77	8	36	5	2	148
Scotland	2	2	2	35	74	2	117

- Generation capacity over the 2011-2030 horizon: National Grid (2011)
- Transmission losses: 7%. (DUKES 2010)
- VOLL: 2,500 £/MWh interrupted (2,904 € /MWh).
- Thermal efficiencies: coal (36.4%), gas (46.7%).
- Gas plants’ profit margin: 6.56 € /MWh (from ICE London, 01/12/09 - 30/11/10)
- Drift & volatility of nodal demands: Jan 2002 – Mar 2011 (DECC)
- Drift & volatility of load factor for wind (Apr 2006 – Dec 2010), hydro (Jan 1997 – Mar 2011), and pumped storage (Jan 1998 – Mar 2011)
- Price processes: futures prices of coal & gas (EEX Leipzig), CO2 (ICE London).

Estimation of each stochastic process

- Loads:

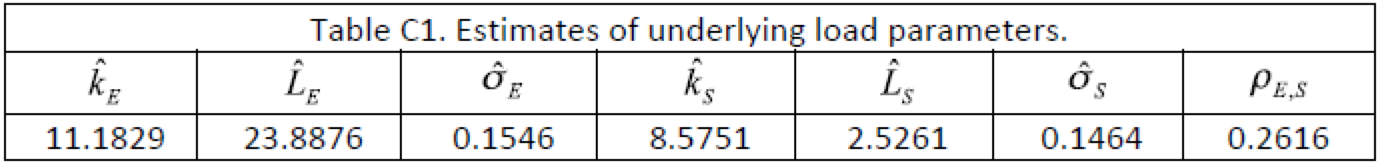


Table C1. Estimates of underlying load parameters.

$\hat{k}_E$	$\hat{L}_E$	$\hat{\sigma}_E$	$\hat{k}_S$	$\hat{L}_S$	$\hat{\sigma}_S$	$\rho_{E,S}$
11.1829	23.8876	0.1546	8.5751	2.5261	0.1464	0.2616

- Wind:

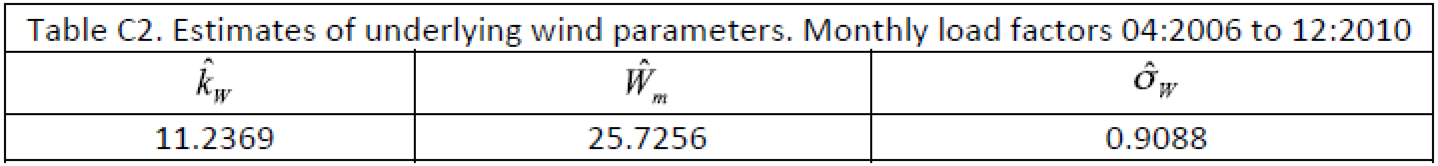


Table C2. Estimates of underlying wind parameters. Monthly load factors 04:2006 to 12:2010

$\hat{k}_W$	$\hat{W}_m$	$\hat{\sigma}_W$
11.2369	25.7256	0.9088

- Hydro:

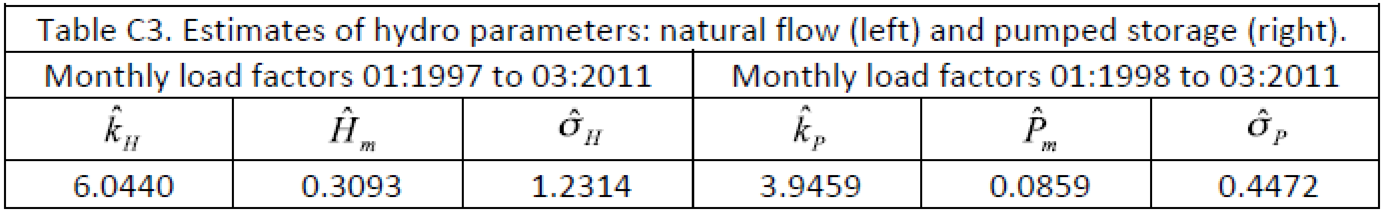


Table C3. Estimates of hydro parameters: natural flow (left) and pumped storage (right).

Monthly load factors 01:1997 to 03:2011			Monthly load factors 01:1998 to 03:2011		
$\hat{k}_H$	$\hat{H}_m$	$\hat{\sigma}_H$	$\hat{k}_P$	$\hat{P}_m$	$\hat{\sigma}_P$
6.0440	0.3093	1.2314	3.9459	0.0859	0.4472

- Prices:

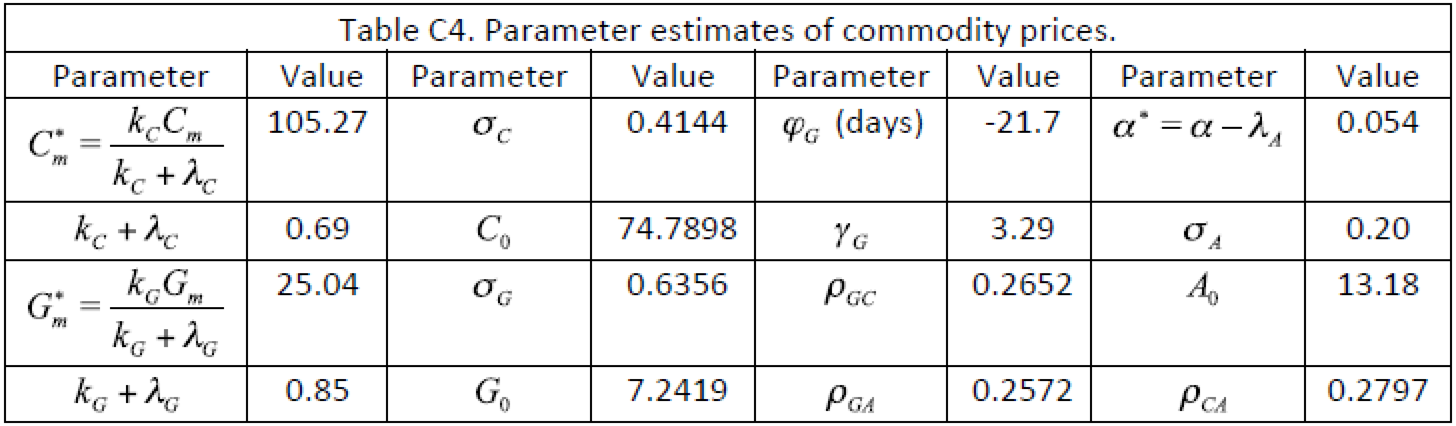
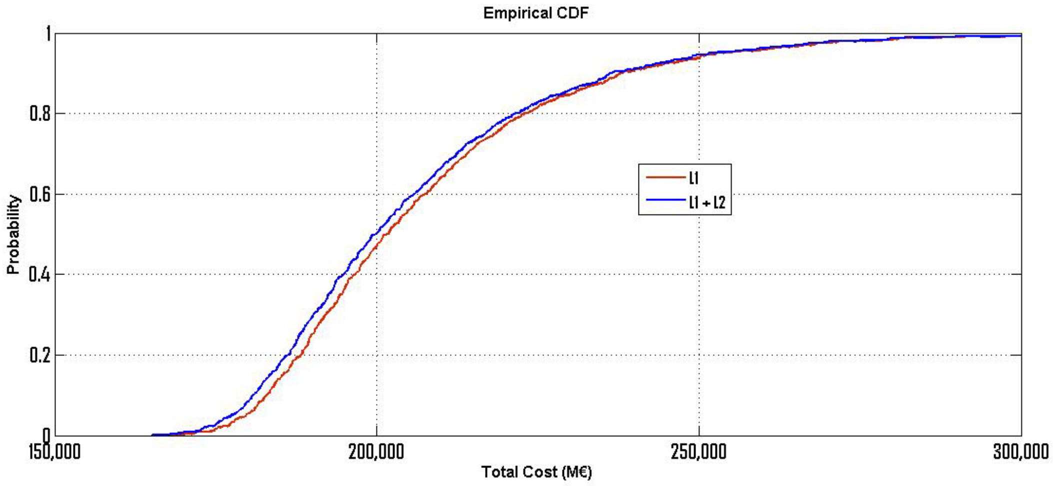
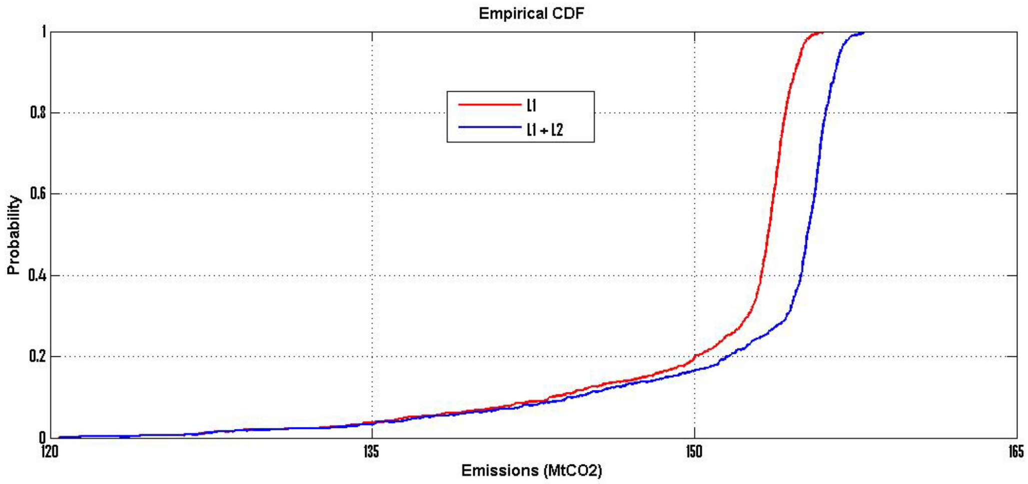


Table C4. Parameter estimates of commodity prices.

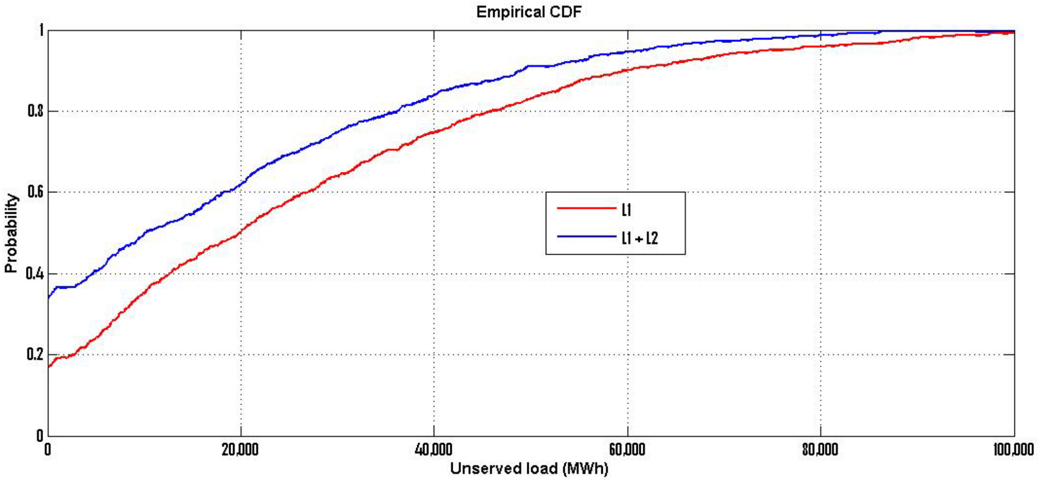
Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
$C_m^* = \frac{k_C C_m}{k_C + \lambda_C}$	105.27	σ_C	0.4144	φ_G (days)	-21.7	$\alpha^* = \alpha - \lambda_A$	0.054
$k_C + \lambda_C$	0.69	C_0	74.7898	γ_G	3.29	σ_A	0.20
$G_m^* = \frac{k_G G_m}{k_G + \lambda_G}$	25.04	σ_G	0.6356	ρ_{GC}	0.2652	A_0	13.18
$k_G + \lambda_G$	0.85	G_0	7.2419	ρ_{GA}	0.2572	ρ_{CA}	0.2797

Base case: no load growth





Base case: no load growth (cont’d)



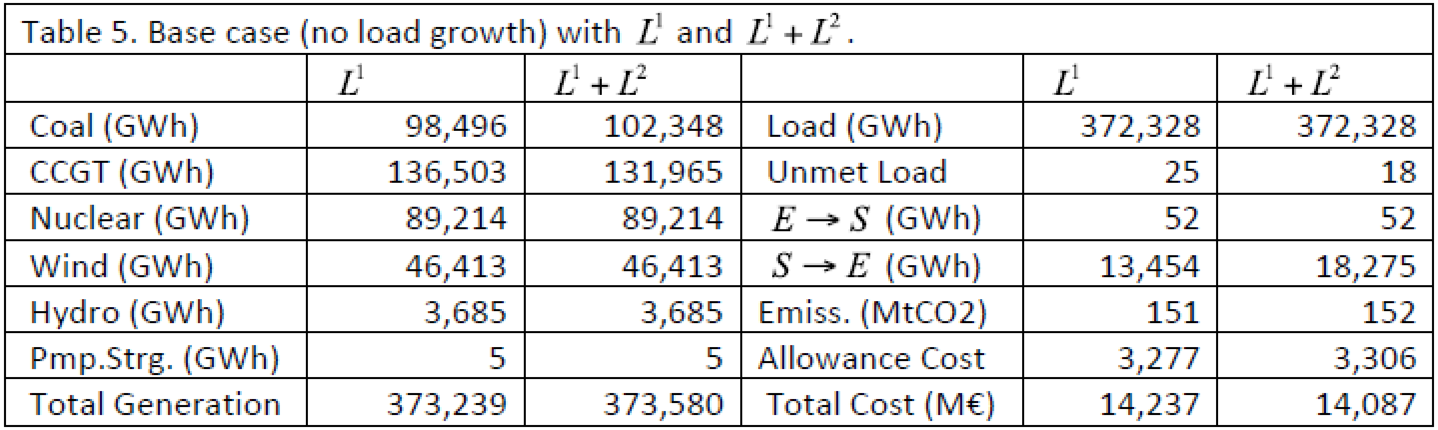


Table 5. Base case (no load growth) with L^1 and $L^1 + L^2$.

	L^1	$L^1 + L^2$		L^1	$L^1 + L^2$
Coal (GWh)	98,496	102,348	Load (GWh)	372,328	372,328
CCGT (GWh)	136,503	131,965	Unmet Load	25	18
Nuclear (GWh)	89,214	89,214	$E \rightarrow S$ (GWh)	52	52
Wind (GWh)	46,413	46,413	$S \rightarrow E$ (GWh)	13,454	18,275
Hydro (GWh)	3,685	3,685	Emiss. (MtCO2)	151	152
Pmp.Strg. (GWh)	5	5	Allowance Cost	3,277	3,306
Total Generation	373,239	373,580	Total Cost (M€)	14,237	14,087

Sensitivity analysis: load growing at 2 %

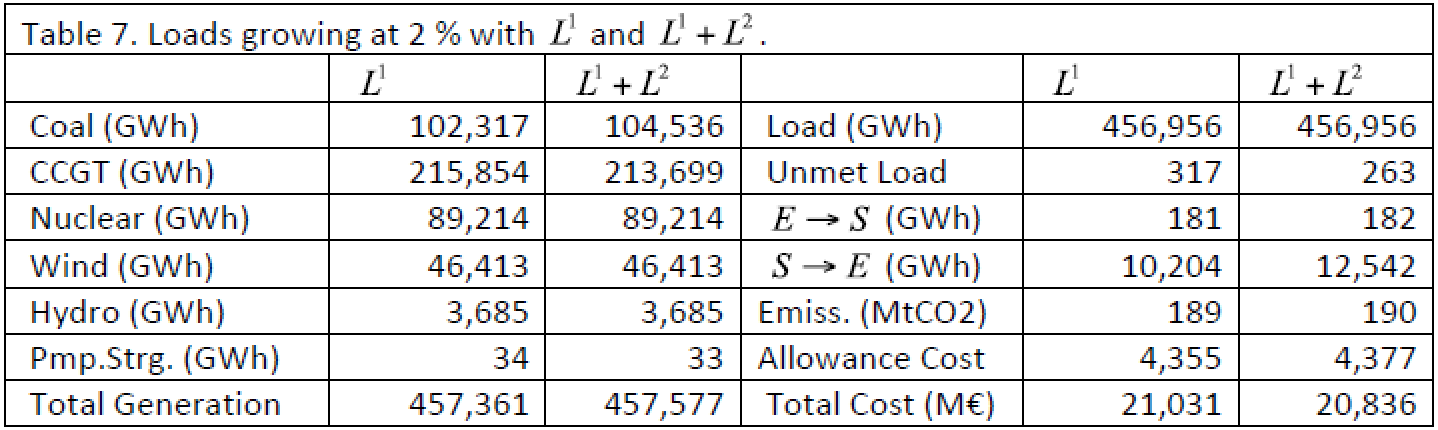


Table 7. Loads growing at 2 % with L^1 and $L^1 + L^2$.

	L^1	$L^1 + L^2$		L^1	$L^1 + L^2$
Coal (GWh)	102,317	104,536	Load (GWh)	456,956	456,956
CCGT (GWh)	215,854	213,699	Unmet Load	317	263
Nuclear (GWh)	89,214	89,214	$E \rightarrow S$ (GWh)	181	182
Wind (GWh)	46,413	46,413	$S \rightarrow E$ (GWh)	10,204	12,542
Hydro (GWh)	3,685	3,685	Emiss. (MtCO2)	189	190
Pmp.Strg. (GWh)	34	33	Allowance Cost	4,355	4,377
Total Generation	457,361	457,577	Total Cost (M€)	21,031	20,836

Sensitivity analysis: nuclear fleet cut in 50 %

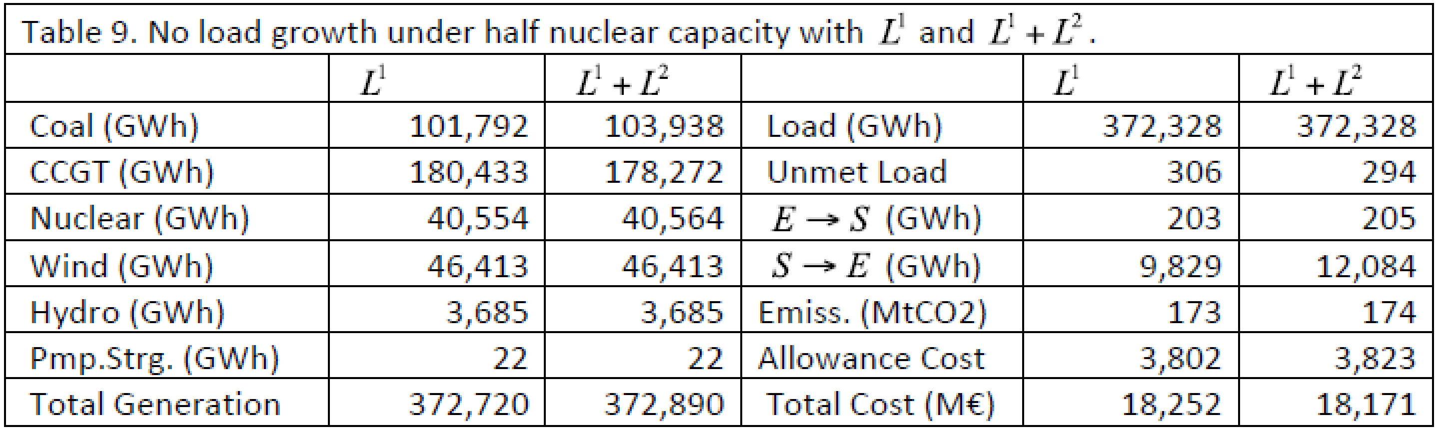


Table 9. No load growth under half nuclear capacity with L^1 and $L^1 + L^2$.

	L^1	$L^1 + L^2$		L^1	$L^1 + L^2$
Coal (GWh)	101,792	103,938	Load (GWh)	372,328	372,328
CCGT (GWh)	180,433	178,272	Unmet Load	306	294
Nuclear (GWh)	40,554	40,564	$E \rightarrow S$ (GWh)	203	205
Wind (GWh)	46,413	46,413	$S \rightarrow E$ (GWh)	9,829	12,084
Hydro (GWh)	3,685	3,685	Emiss. (MtCO2)	173	174
Pmp.Strg. (GWh)	22	22	Allowance Cost	3,802	3,823
Total Generation	372,720	372,890	Total Cost (M€)	18,252	18,171

Conclusions

- Need for transmission network expansions in a number of markets.
- Uncertainty all around: permissions, final cost, expected benefits.
- Valuation model that accounts for physical and economic uncertainties.
- Model combines optimization with simulation. Use of prices on futures markets enables risk-neutral valuation.
- Demonstration by example: the Western subsea HVDC link in Great Britain.
- We simulate whole distribution of effects over the whole useful lifetime of project.
- Base case (flat load): the new corridor entails significant savings in system cost. Congestion benefits are sizeable, while reliability benefits play a minor role.

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