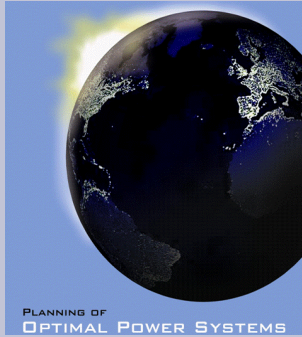


PLANNING OF POWER SYSTEM RESERVES

Asko Vuorinen



Reliability terms



Reliability terms

Forced outage rate (FOR)

$$\text{FOR} = \text{FOH} / (\text{FOH} + \text{SH}) \times 100 \%$$

FOH = forced outage hours

SH = service hours



Reliability terms, continued



Equivalent forced outage rate (EFOR)

$$\text{EFOR} = \frac{\text{FOH} + \text{EFDH}}{\text{FOH} + \text{SH} + \text{EFDH}} \times 100 \%$$

EFDH = equivalent forced derated hours
(output reductions + forced hours)



Reliability terms, continued

Equivalent forced outage rate demand

$$EFOR_d = \frac{f \times FOH + f_p \times EFDH}{SH + f \times FOH} \times 100 \%$$

$$f = (1/r + 1/T)/(1/r + 1/T + 1/D)$$

$$f_p = SH/AH$$

AH= available hours

r = average forced outage duration = FOH/number of forced outages

T = average times between calls of unit to run

D = average run time = SH/number of successful starts



Reliability terms, continued



Starting reliability (SR)

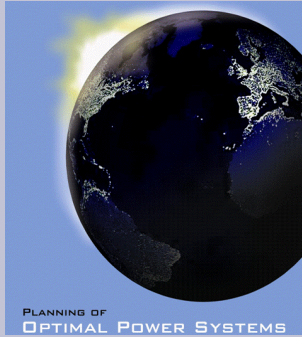
$$\text{SR} = \frac{\text{actual unit starts}}{\text{attempted starts}} \times 100 \%$$



US Statistics (1999-2003)*

	EFORd	SR
Conventional plants	6.2%	98.4%
- Coal-fired plants	6.4%	97.4%
- Oil-fired plants	5.7%	99.4%
- Gas-fired plants	5.9%	99.2%
Nuclear plants	5.4%	98.5%
Hydro plants	3.6%	99.5%
Combined cycles	5.6%	97.6%
Gas turbines (GT)	7.5%	95.5%
Aero-derivative GT	6.8%	97.2%
Diesel engines	5.4%	99.4%

*Source: North American Reliability Council (NERC)



Reliability of power system



Probability that exactly m of n units are in operation



$$P(M=m | n, R) = \frac{n!}{m! (n-m)!} R^m (1-R)^{n-m}$$

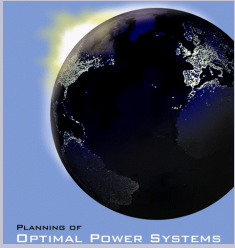
n = number of units in the system

$n! = 1 \times 2 \times 3 \times \dots \times n$

m = number of units in operation

$m! = 1 \times 2 \times 3 \times \dots \times m$

R = reliability of an unit = 1 - EFORd



Probability that at least m of n units are in operation



$$P(M=m | n, R) = \sum \frac{n!}{m! (n-m)!} R^m (1-R)^{n-m}$$

n = number of units in the system

n! = 1 x 2 x 3 x ... x n

m = number of units in operation

m! = 1 x 2 x 3 x ... x m

R = reliability = 1 - EFORd



SYSTEM RELIABILITY

$R = 95\%$ ($EFOR_d = 5\%$)



Number of units n	3	4	5	10	20	100
Units in operation						
n	0.8574	0.8145	0.7738	0.5987	0.3585	0.0059
n-1	0.9928	0.9859	0.9774	0.9139	0.7358	0.0371
n-2	0.9999	0.9995	0.9988	0.9885	0.9245	0.1183
n-3		0.9999	0.9999	0.9989	0.9841	0.2578
n-4				0.9999	0.9974	0.4360
n-5					0.9997	0.6160
n-6					0.9999	0.7660
n-7						0.8720
n-13						0.9995
n-15						0.9999



Normal utility system*

Reliability target ($R_s = 99.9\%$)



System	Reserve need
3 x 100 %	200 %
4 x 50 %	100 %
5 x 33 %	67 %
13 x 10 %	30 %
25 x 5 %	25 %
113 x 1 %	13 %

*Unit reliability = 95 %



Modern utility system*

Reliability target $R_s = 99.99\%$



System	Reserve need
4 x 100 %	300 %
5 x 50 %	150 %
14 x 10 %	40 %
26 x 5 %	30 %
115 x 1 %	15 %

*Unit reliability = 95 %



Reserve margin (RM)

$$RM = \frac{\text{Capacity-Peak load}}{\text{Peak load}} = \frac{1 - R + Z \times \sigma/n}{R - Z \times \sigma/n}$$

R = reliability of unit

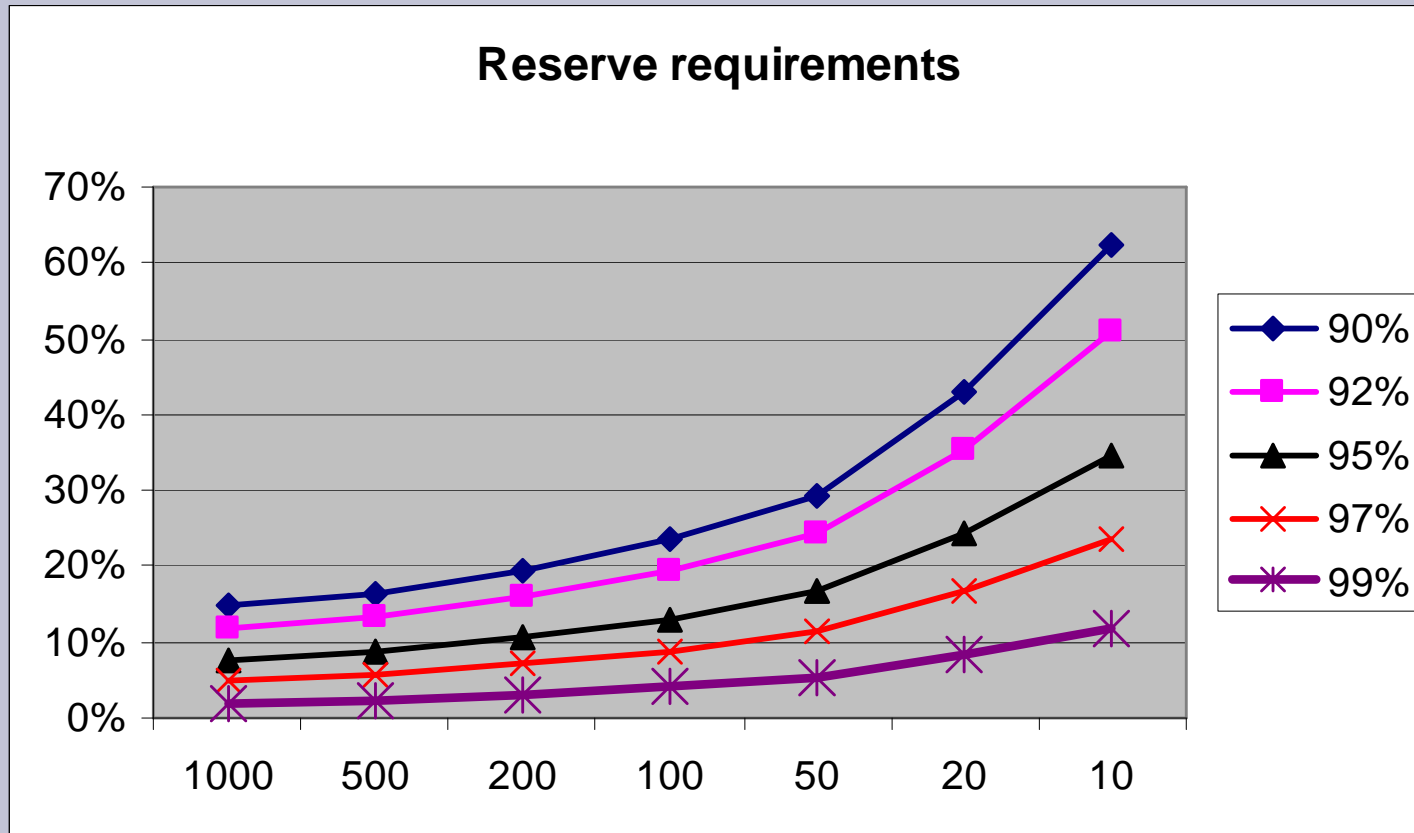
Z = level of confidence

Sigma = standard deviation of reliability

n = number of units in the system



Reserve requirements at three sigma level ($R_s = 99.7\%$)

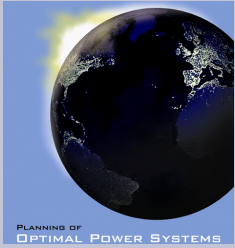




General

Utility system needs less reserves, if the number of units (n) will grow and if the reliability of units (R) increases

System with 100 units needs 10 – 20 % reserves when the reliability of units varies from 92 to 97 %



Reserve requirements with one large and several small units

Simplified formula

$$RR = \sum ((1-R) \times P_{ui}) + P_{\max}$$

Where

RR = reserve requirement

P_{\max} = largest unit in the system

R = reliability of the other units

P_{ui} = output of unit i

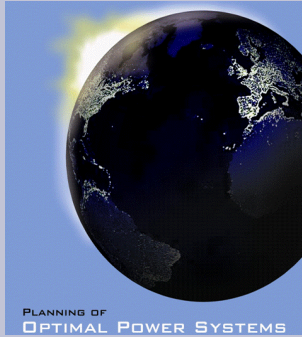


Reserve requirements with one large and several small units



If the largest unit is 10 % of system size and the reliability of other units is 5 %, then

$$RR = 5 \% + 10 \% = 15 \%$$



Adequacy of power system capacity



Adequacy of power system capacity



Practical Criteria of Adequacy

$$LAC > MPL$$

Where

LAC = lowest available capacity

MPL = maximum peak load



Adequacy of power system capacity, continued

Lowest available capacity (LAC)=
Total capacity - Unavailability

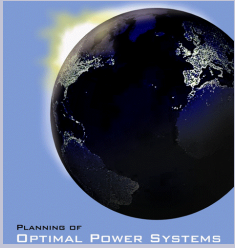
Where

$$\text{Unavailability} = \sum (\text{EFOR}_{di}) + Z \times \sigma_C$$

$\sum(\text{EFOR}_{di})$ = sum of average unavailabilities of power plants

Z = coefficient of confidence (= 1.29 for 90 % confidence)

σ_C = variance of capacity



Adequacy of power system capacity, continued



Maximum peak load = Average peak load + Margin

Where

Average peak load = historical trend

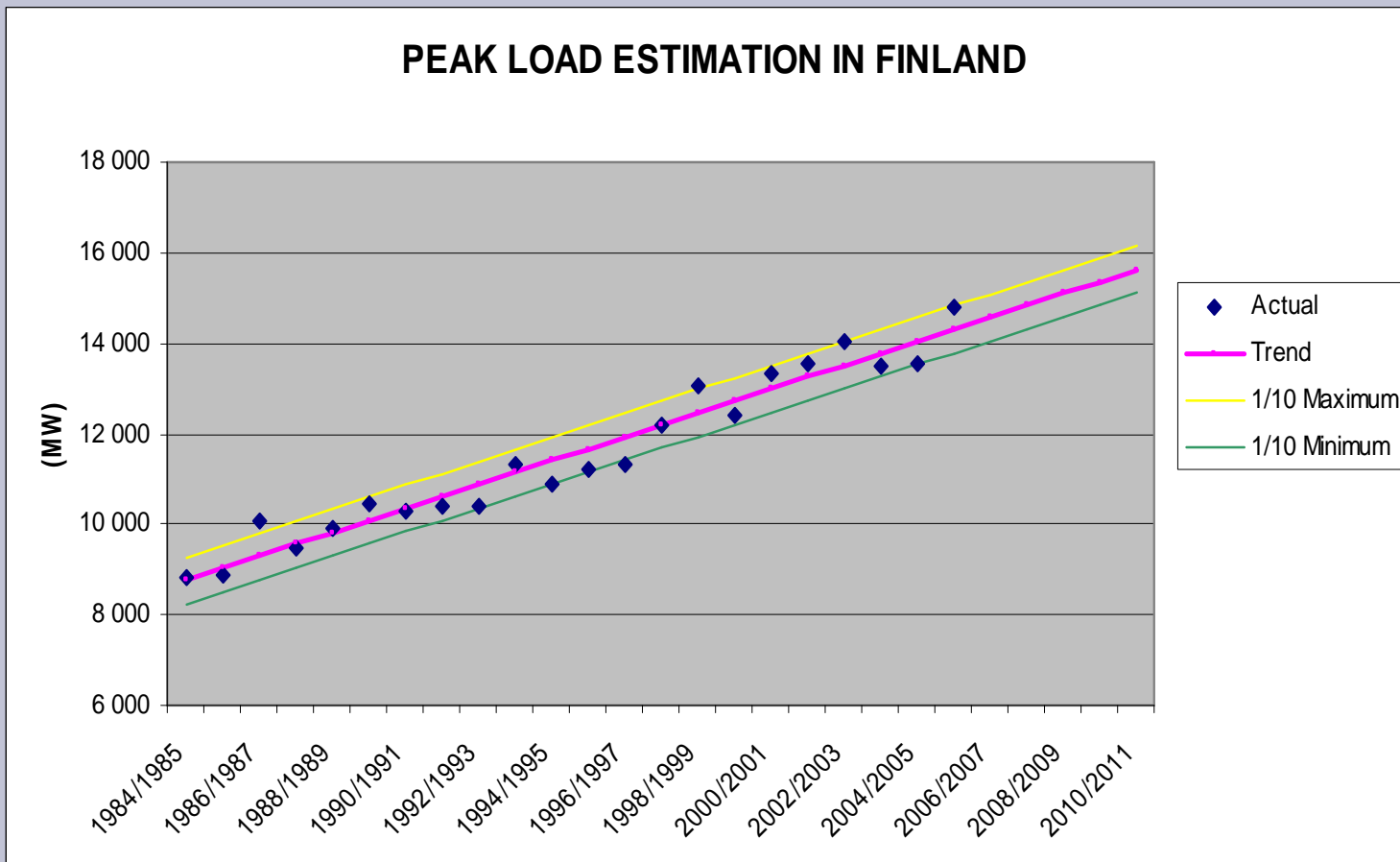
Margin = $Z \times \sigma_{PL}$

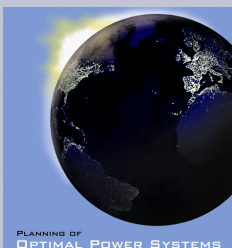
Z = coefficient for confidence (=1.29 for 90% confidence, figures are given in the book)

σ_{PL} = variance from the historical trend



Maximum peak load in Finland (= 1/10 maximum)





Adequacy of capacity in Finland without imports



Winter		2005/6	2009/10	2010/11	Difference
		A	B	C	C - B
<i>Capacity</i>	<i>MW</i>	13650	13950	15550	1600
<i>Average unavailability</i>	<i>MW</i>	-683	-698	-778	-80
<i>1,29 sigma contingency</i>	<i>MW</i>	-483	-485	-661	-177
<i>Available capacity</i>	<i>MW</i>	12485	12768	14111	1343
<i>Peak load (1/10)</i>	<i>MW</i>	-14826	-15 882	-16 146	-264
<i>Capacity deficit</i>	<i>MW</i>	-2341	-3114	-2035	1079
<i>Deficit/Peak load</i>	%	16%	20%	13%	-7%



Planning reserves

$$= \text{Average Unavailability} + Z \times \sqrt{(V_c + V_p)}$$

Where

$$\text{Average Unavailability} = \sum ((1-R_i) \times P_{ui})$$

R_i = reliability of unit i

P_{ui} = output of unit i

Z = level of confidence

V_c = variance of capacity

V_p = variance of peak load



Optimal capacity deficit by value of lost load

Criteria $VOLL = Fc/t + Vc$

Then $t = Fc/(VOLL - Vc)$

Where

$VOLL$ = value of lost load (=5000 €/MWh)

t = hours of load is more than capacity

Fc = fixed costs of peaking plant

Vc = variable costs of peaking power plant



Optimal capacity deficit by value of lost load

With a diesel engine peaking plant

$$t = 68.1 / (5000 - 109) = 13.9 \text{ deficit hours}$$

Loss of load probability (LOLP) =

$$13.9 \text{ hours} / 8760 \text{ h/a} = 0.0014 = 10^{-3}$$

Reliability of power system is then 99.9 %



Optimal reliability targets

National power system = 99.9 %

Interconnected system = 99.99%

Safety related power system = 99.9999%*

- * Can be planned by adding standby diesel engines, which start within one minute when the interconnected system fails (see slide 9 for configurations)



SUMMARY

- Reserve needs become lower by planning systems with smaller and more reliable units
- Largest unit determines the need of reserve capacity, if the unit sizes are unevenly distributed
- The modern electronic age requires higher system reliability figures because everything depends on computers



For details see reference text book
”Planning of Optimal Power Systems”



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Further details and
internet orders see:

www.optimalpowersystems.com

