Technical University of Denmark

Load-following capabilities of nuclear power plants

Nonbøl, Erik

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Load-following capabilities of Nuclear Power Plants

Erik Nonbøl

DTU Nutech
Center for Nuclear Technologies

Outline

- Why load-following
- Modes of power operation
- BWR technique for load-following
- PWR technique for load-following
- Effects on components
- Effects on Economy
- Example of load-following in France and Germany
- Conclusion

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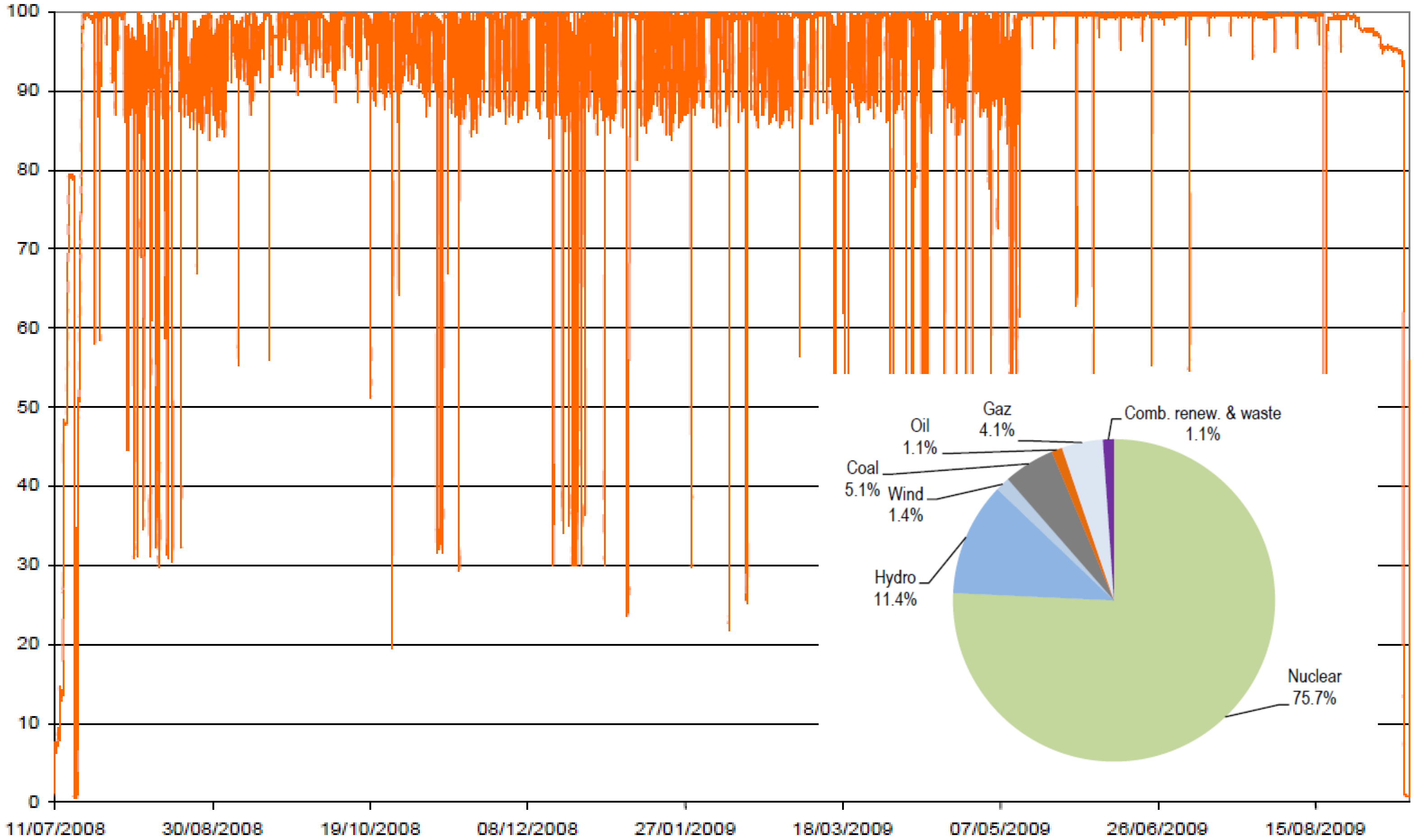
Increasing amount of intermittent energy sources

- Wind
- Solar
- Irregular variations in power supply
- Balancing of supply and demand very difficult
- Suddenly supply of large wind power has lead to negative electricity prices – lower than the variable costs even of NPP in Germany
- The share of electricity from NPP has increased in some countries thus demanded load-following also of these. This is the case in Germany and France

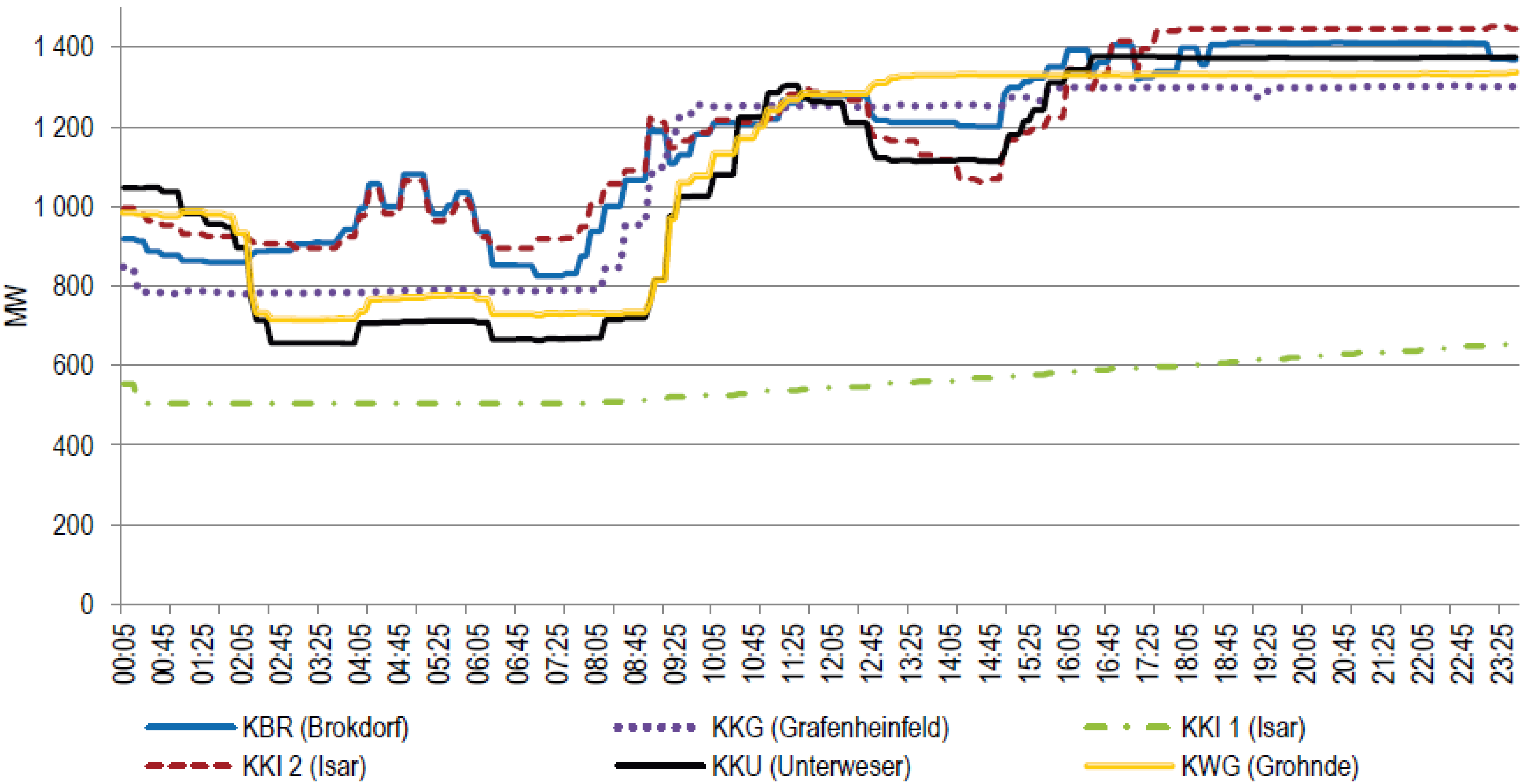
Power history of a French NPP

Figure E.1: Example of a typical power history during a cycle in a EDF reactor (in % of the rated power)



Load-following during 24 hours in Germany

Figure E.2: Example of the electricity generation with some German nuclear power plants.



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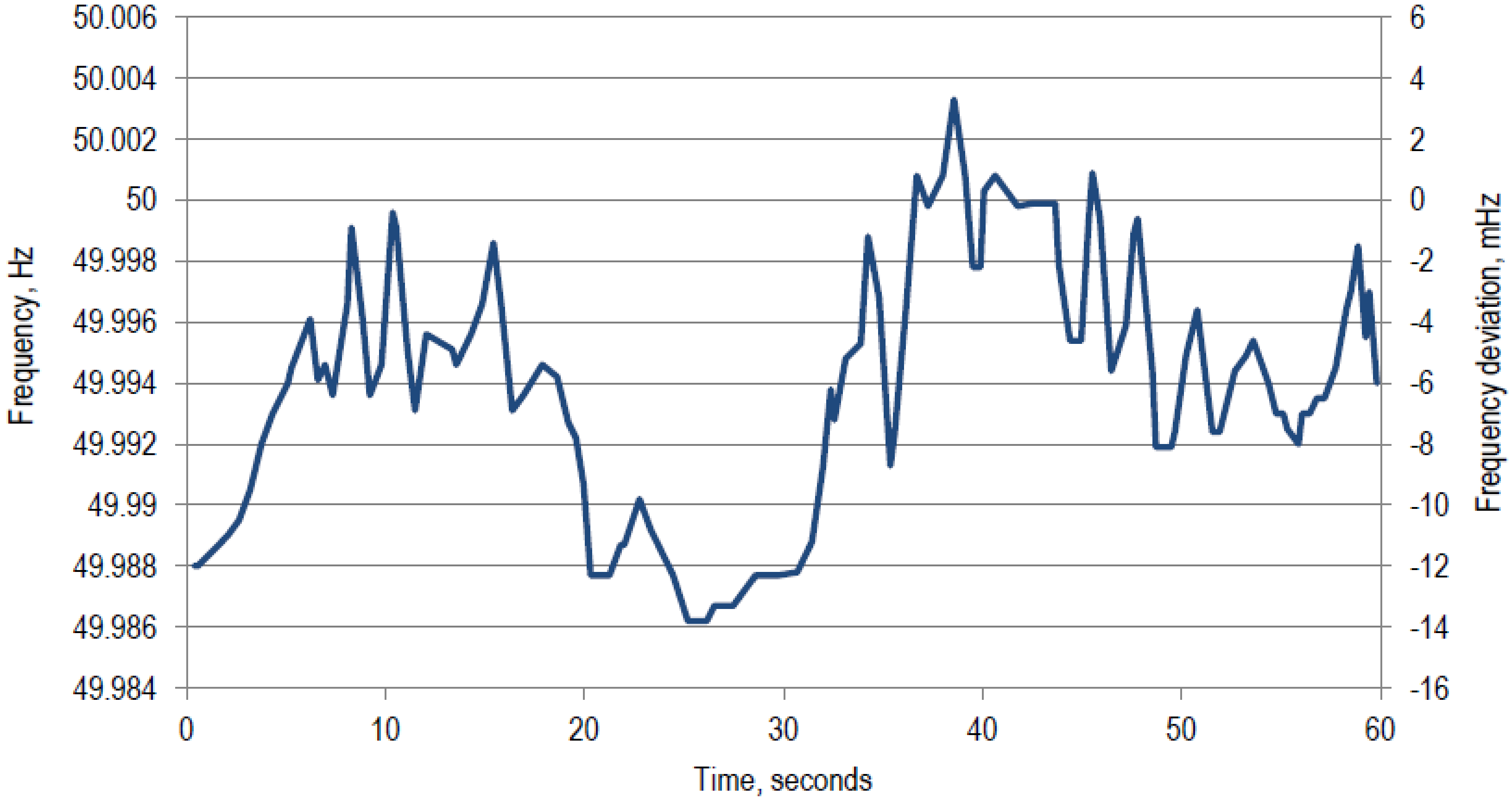
Modes of operation for power plants

- Base-load control mode
  - 100 % P_r
- Primary frequency control mode
  - $\pm$ 2% P_r within 2-30 s
- Secondary frequency control mode
  - $\pm$ 5% P_r within 1-30 min
- Load-following mode (part of EUR)
  - Daily–load cycling operation between 50% - 100% of reference power at a rate of 3-5 % pr/min

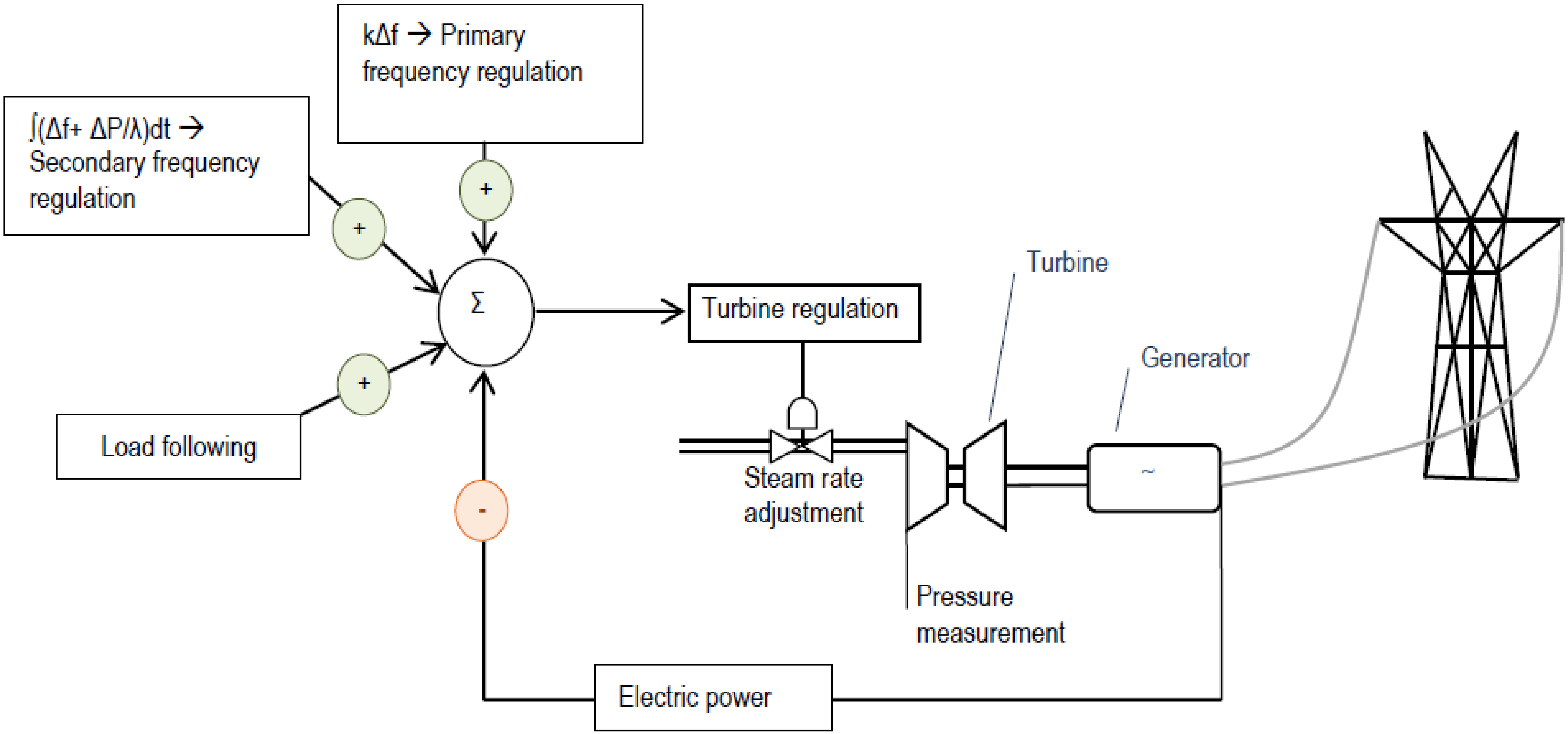
Frequency variation on the European grid



Minimum requirements of power regulation EUR

- Daily–load cycling operation between 50% - 100% of rated power at a rate of 3-5 % pr/min
- A lower level of minimum load can be requirered of the grid operator during nights and weekends
- The points above shall be fulfilled during 90 % of the fuel cycle
- Load scheduled variations from full power to minimum and back at a frequence of:
  - 2 per day
  - 5 per week

Turbine control in power regulation



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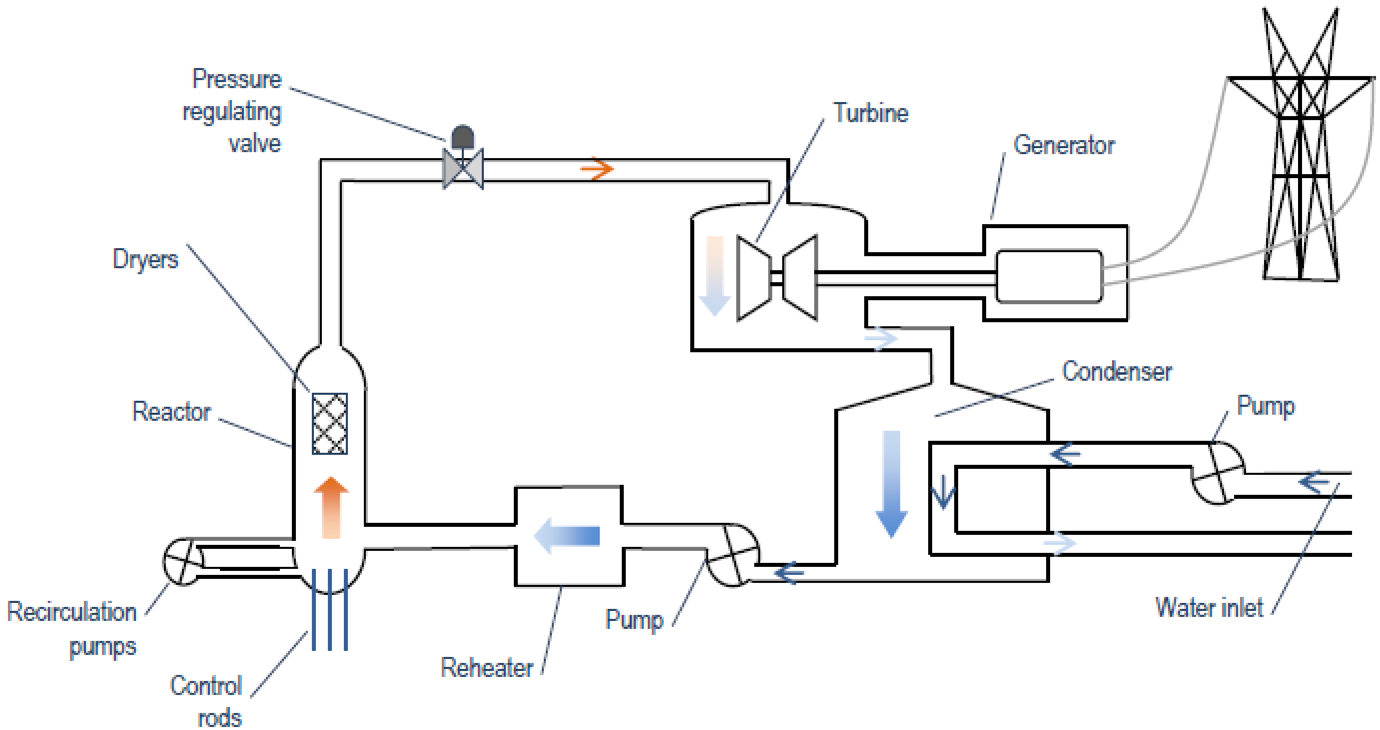
Power regulation of BWR

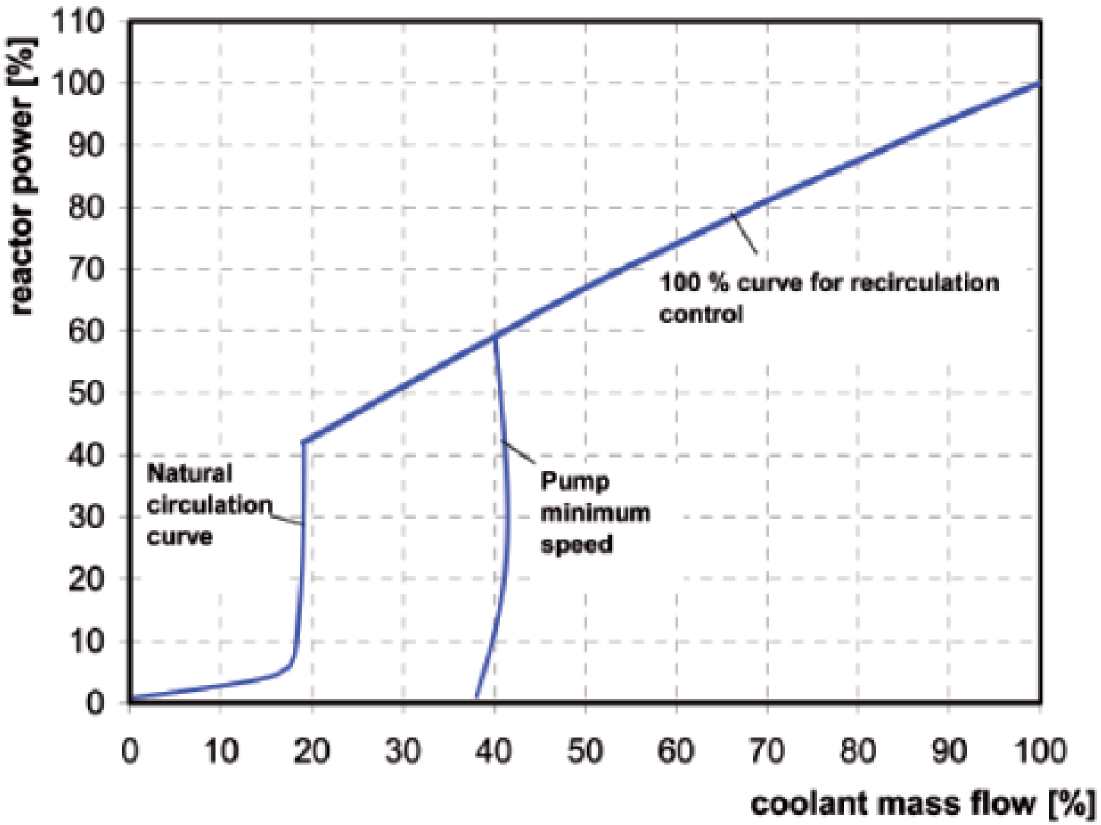
- Recirculation flow control by changing velocity of pumps
  - Increased velocity → increased moderator density → increased power - and visa versa
  - Very fast – ramps of 10%P_r /min within 40-100% P_r
  - Power distribution unchanged
- Control rod movements
  - Power distribution disturbed
  - Risk for thermal stresses
  - Pellet-cladding interactions

All the time stability of the reactor is sustained through undermoderation

Simple layout of a BWR



Power regulation of BWR



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Power regulation of PWR

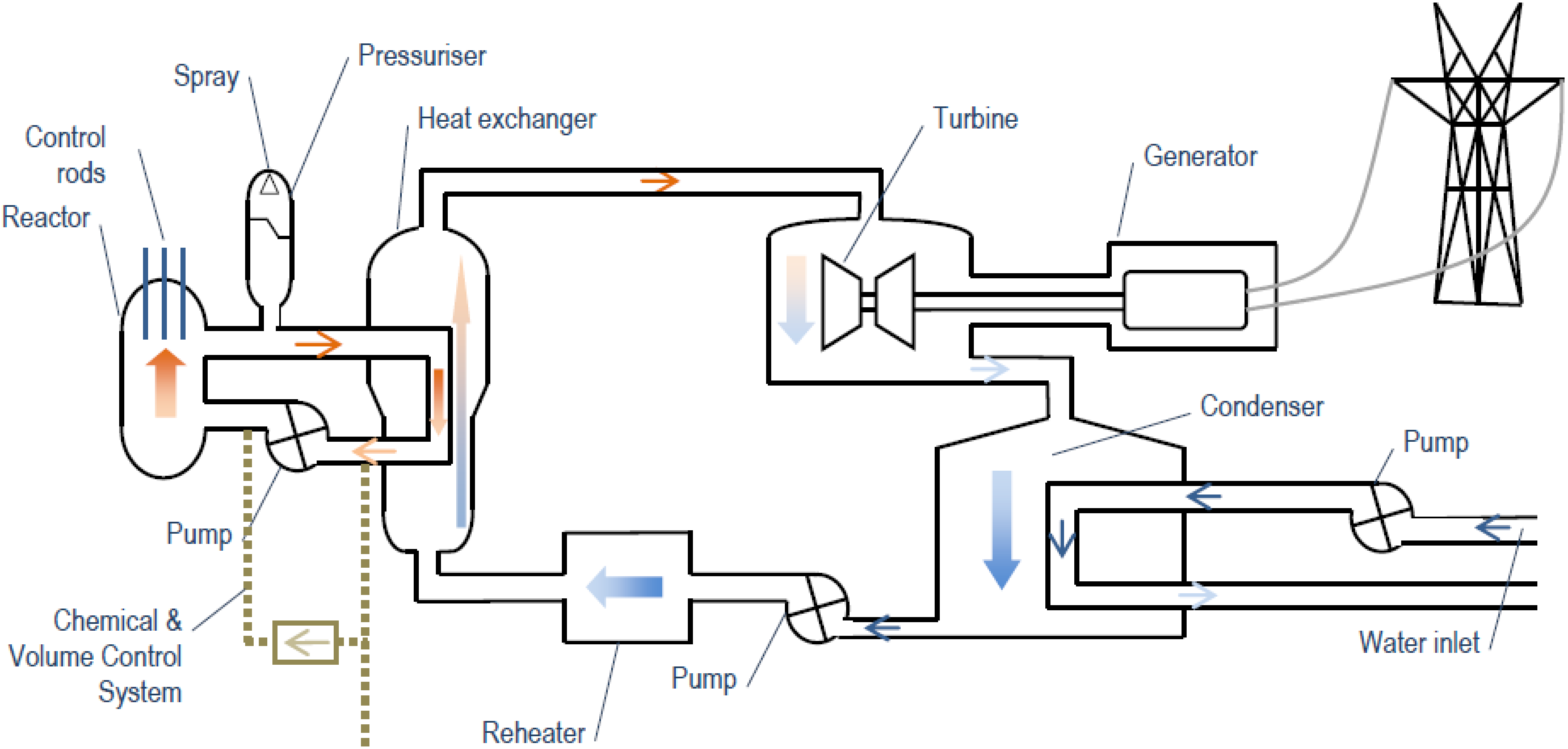
- Control rod movements
  - Use of gray control rods to minimize local power peaks during power change
  - Rather fast regulation – ramps of 5%P_r /min within 40-100% P_r
  - Power distribution deformed
- Adjusting boron concentration in coolant
  - Power distribution undisturbed
  - Slow regulation - cannot participate in frequency control
  - Mainly used for compensating burnup and xenon effects on reactivity

Power regulation of PWR - continued

- At the end of a fuel cycle (after 10 months of operation) the manoeuvrability is decreased due to reduced excess reactivity (fuel burnup)
  - Control rods in upper position
  - Boron concentration almost zero
- ^{135}Xe poisoning is a growing problem at the end of fuel cycle – can cause prolonged shutdown times
- Therefore the load-following requirements of NPP are reduced at the end of fuel cycle

All the time stability of the reactor is sustained through undermoderation - even with boron in the coolant

Simple layout of a PWR



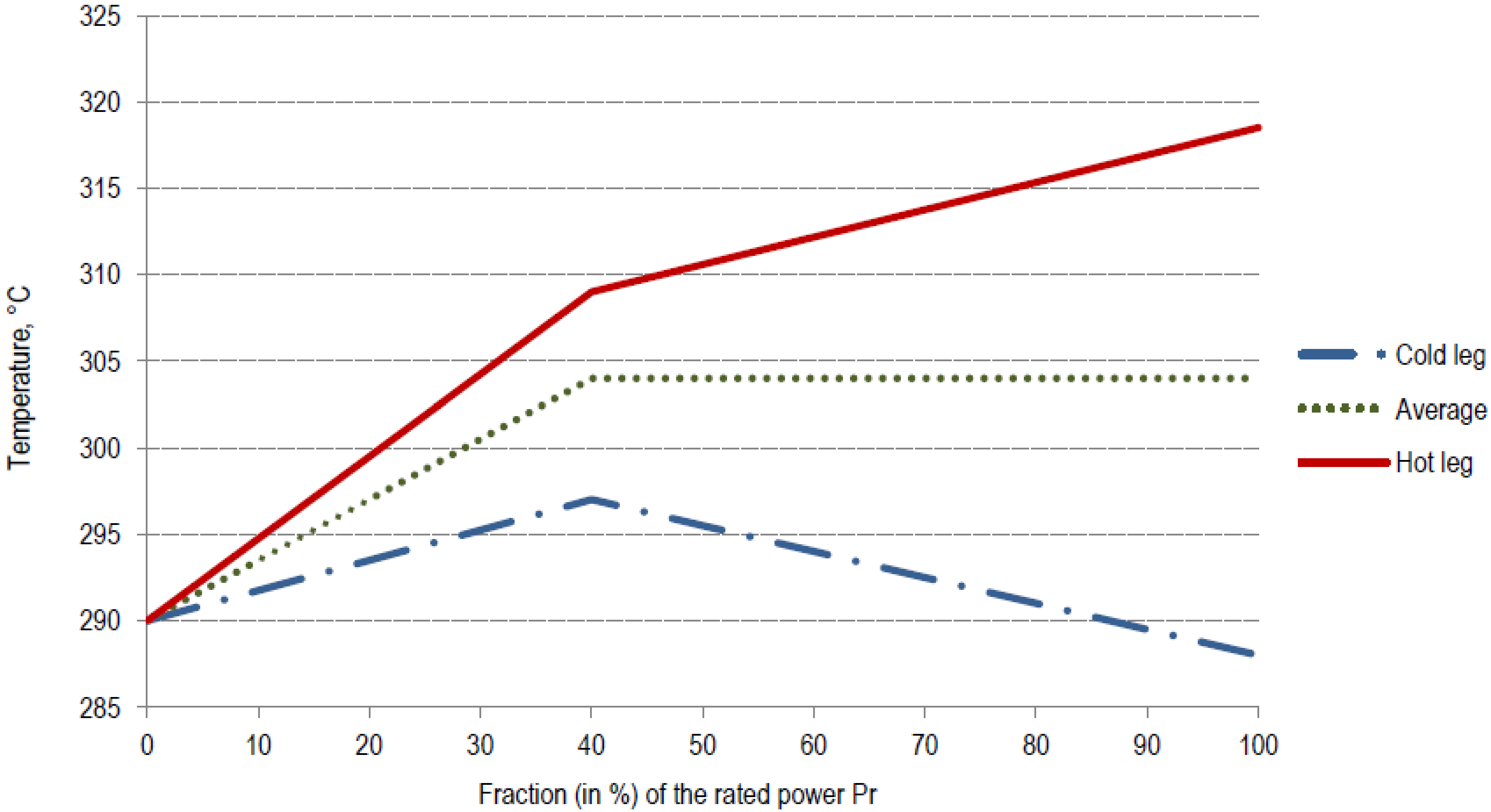
Modes of regulation for PWR

1) Average temperature in the primary circuit (reactor) constant, flow constant, temperature increase over core ΔT vary
   - Average = $(T_{hot\ leg} + T_{cold\ leg}) \times 0.5$
   - $\Delta T = T_{hot\ leg} - T_{cold\ leg}$
   - Pressure of secondary system (steam generator) vary

2) Pressure in secondary system constant, ($T_{cold\ leg}$ constant) flow constant, temperature increase over core ΔT vary
   - Increased power demand→increased average temp in core

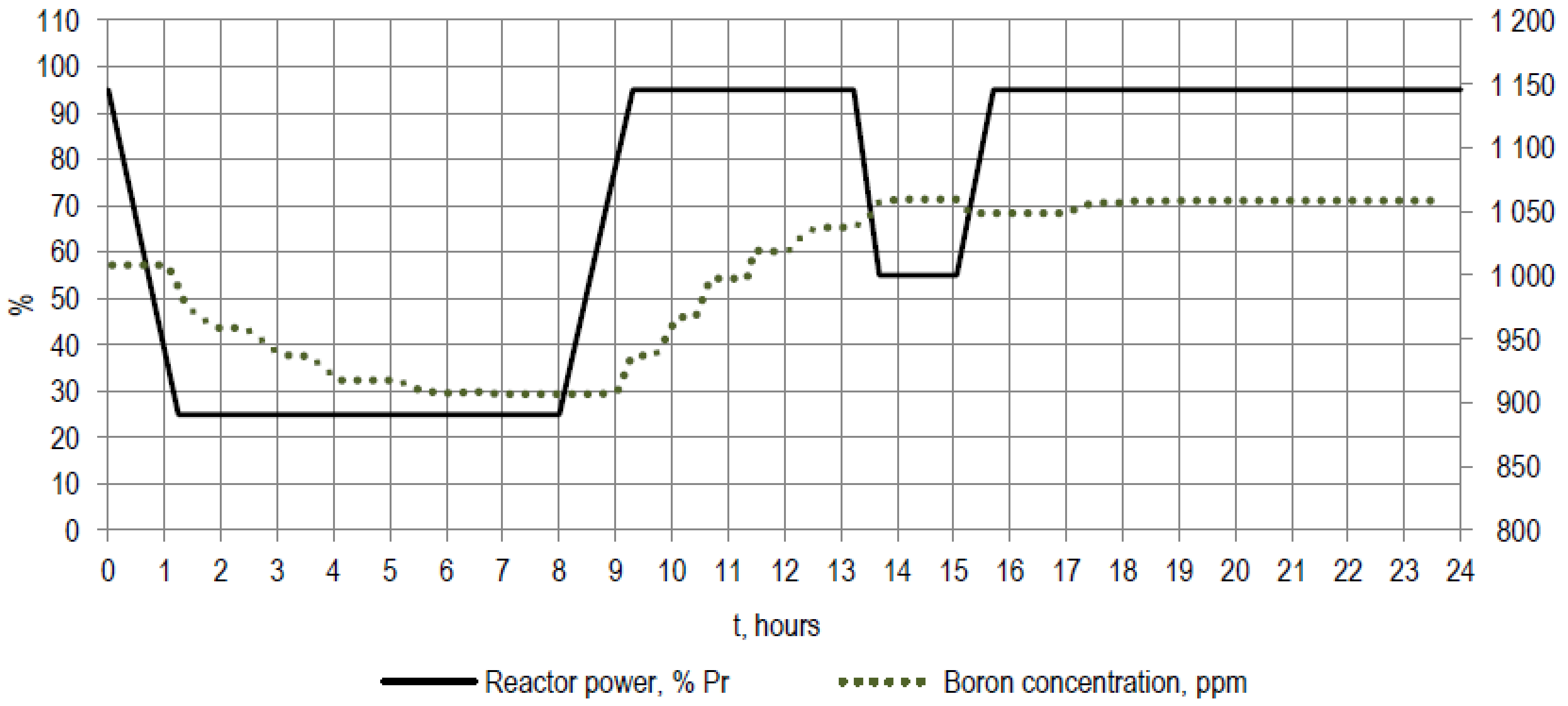
3) Combination of 1) and 2)

Example of regulation of EPR



Load following where boron also participate

Figure 3.11: Example of load following in a operational mode X (N4 reactor)



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Effects on components

- Repeated local temperature variations with large gradients can lead to stress corrosion cracking of critical mechanical components – valves, bends, joints, nozzles
- Increased monitoring of fatigue strength for critical components
- Increased maintenance costs
- Increased risks of pellet cladding interaction through fast change of linear heat generation in the fuel
  - different expansion coefficients of clad and fuel can thus lead to failure of the cladding if the rate of power variations is not limited
- Grey control rods and boron regulation minimize the risk of too fast power changes

Effects on components - continued

- Effective core monitoring system of local power density is necessary to assure operation within safety limits

- Experiences from France and Germany show the effects on fuel can be minimized when operating within the defined limits set by EUR

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Effects on economy

- NPP normally operate as baseload due to high fixed costs and low variable costs
- Load-following operation leads to reduced load factor LF
  - LF=EG/REG, EG is the power delivered to the grid and REG is the reference power
- Increased maintenance costs
- Economically it is best to run NPP as baseload with high LF – however in France the load factor only is reduced with 1.2 % caused by load-following

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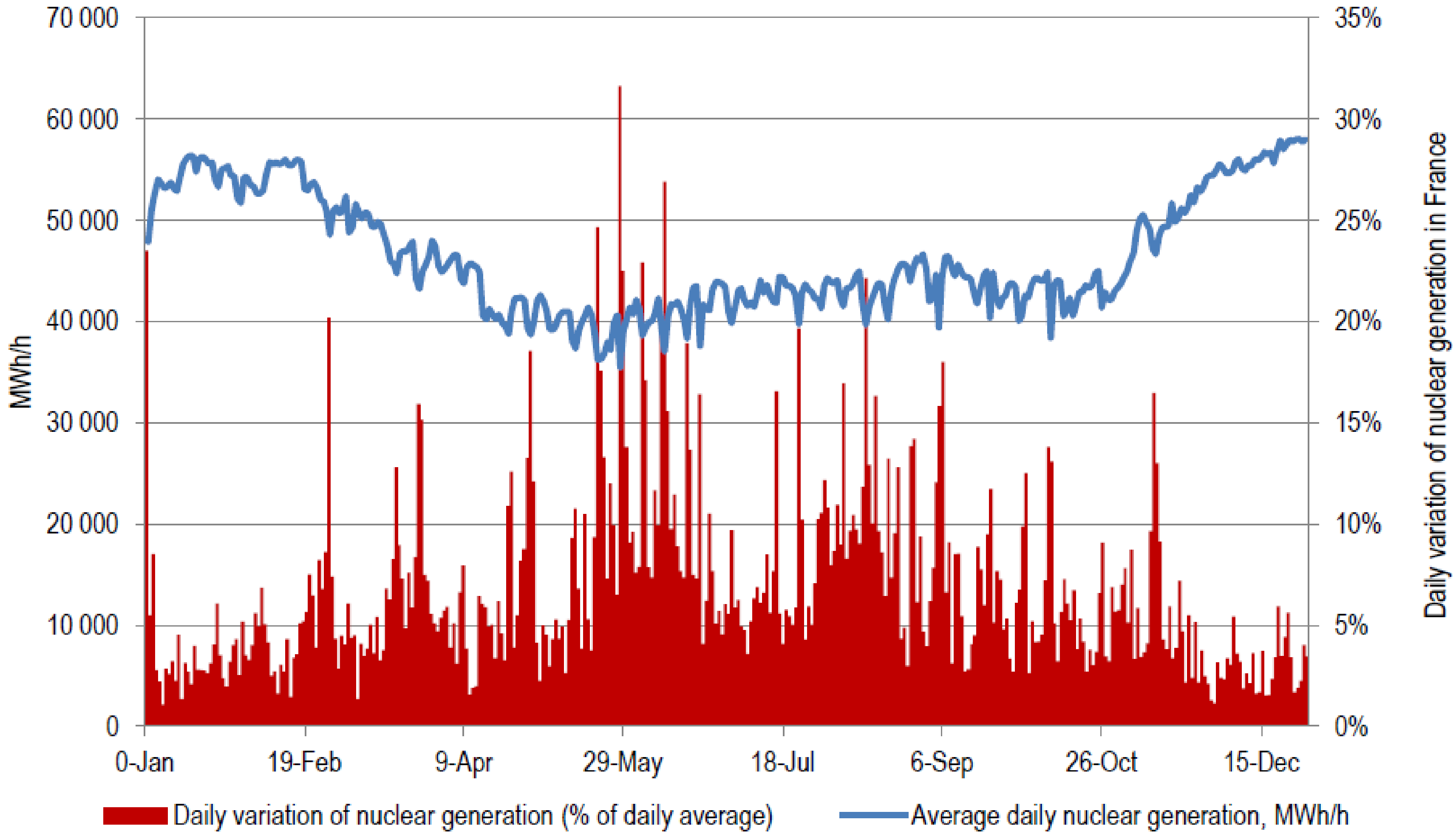
Variation of nuclear generation in France for 2010



$$[\text{Daily variation of nuclear generation G}] = \frac{\max\limits_{24\text{ h}} \text{G} - \min\limits_{24\text{ h}} \text{G}}{\underset{24\text{ h}}{\text{Average}}\,\text{G}}$$

Typically load-following of and EDF NPP

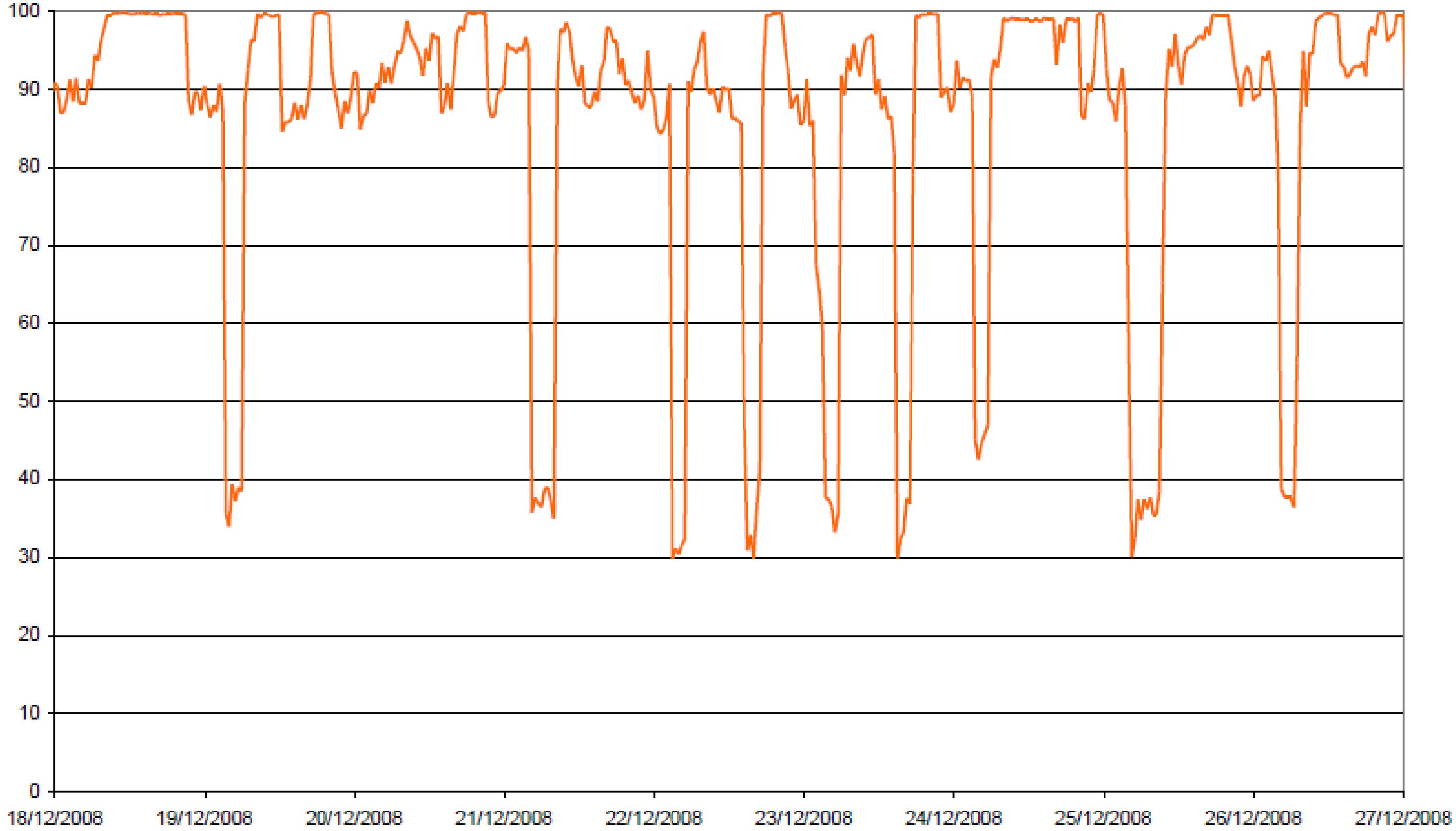
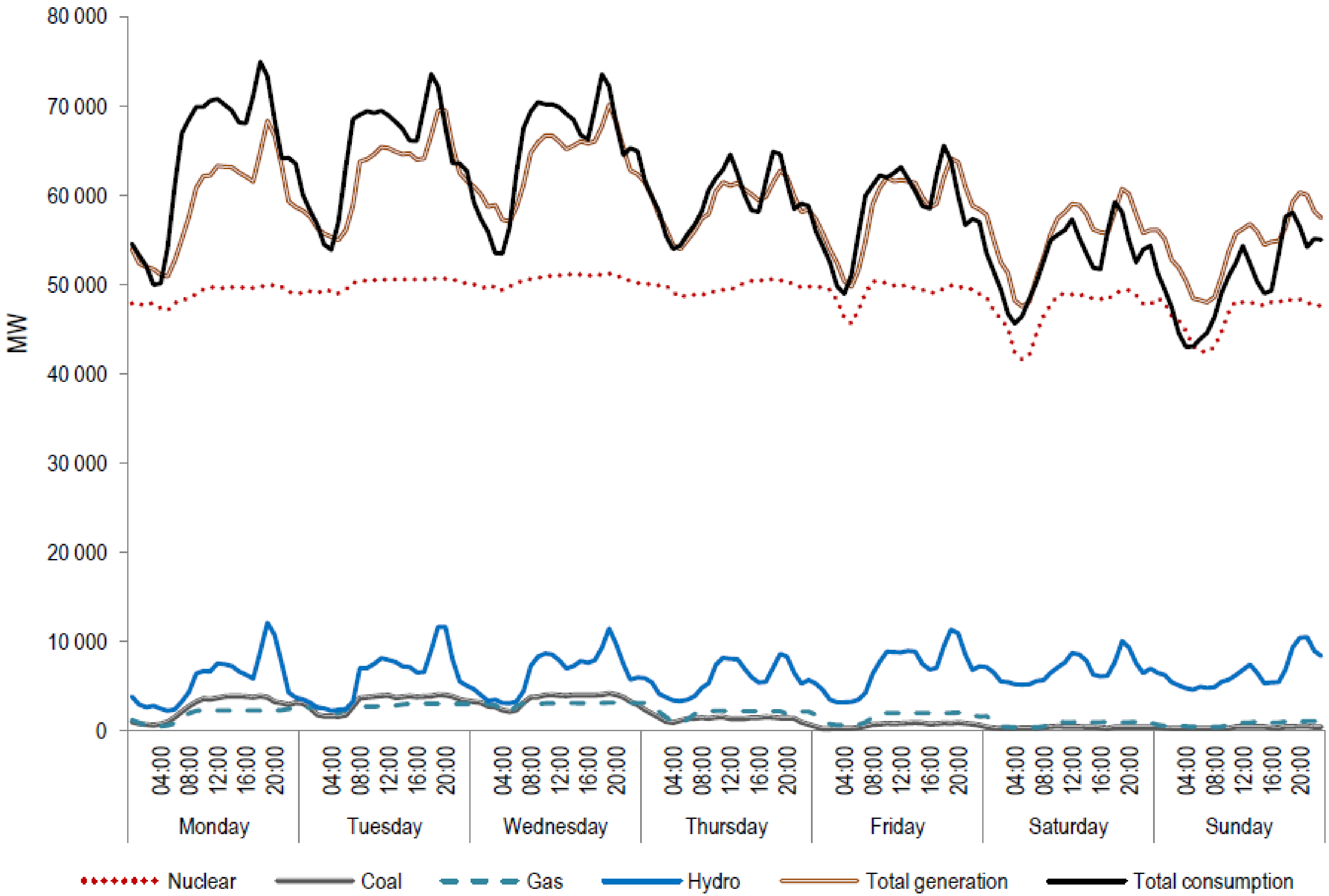


Figure 1.3: Example of the electricity generation in France during 2 weeks in November, 2010



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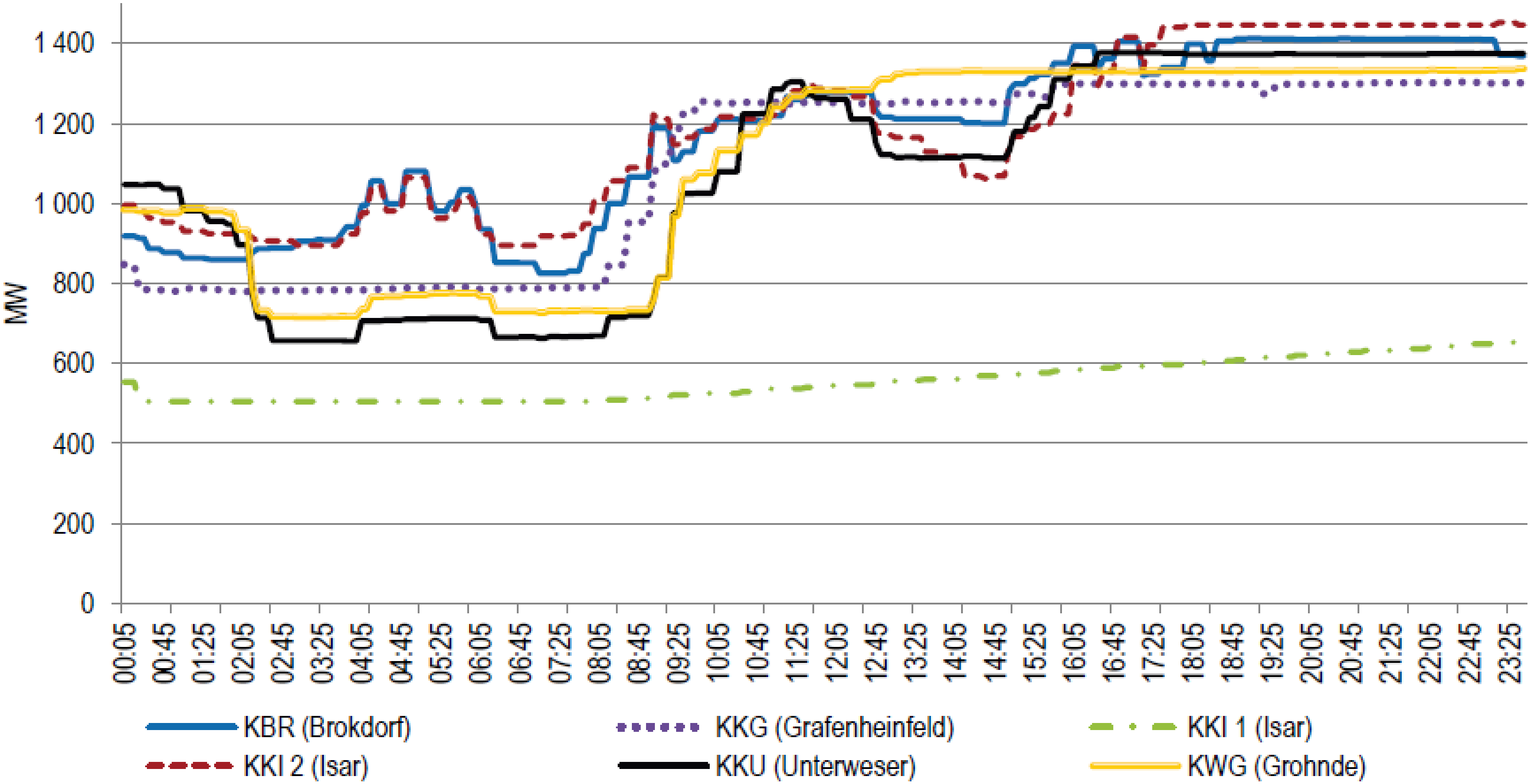

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Conclusion

- It has been shown that technically NPP can participate in load-following as well as coal fired power plants with almost same response time and without jeopardizing the safety
- Economically however, base load operation is preferable due to high investment costs and minimal fuel costs
- Never the less France has proved load-following can be carried out with only 1.2 % decrease in load factor and corresponding small effect on economy
- It is foreseen that future generation of NPP will have increased load-following capabilities mainly because of faster control systems and more advanced fuel design

Comparison of power plants load-following capacities

Table 1: **A comparative analysis of dispatchable power plants' load-following capacities**

	Start-up time	Maximal change in 30 sec	Maximum ramp rate (%/min)
Open cycle gas turbine (OCGT)	10-20 min	20-30%	20%/min
Combined cycle gas turbine (CCGT)	30-60 min	10-20%	5-10%/min
Coal plant	1-10 hours	5-10%	1-5%/min
Nuclear power plant	2 hours - 2 days	up to 5%	1-5%/min

Source: EC JRC, 2010 and NEA, 2011.

Source of information

1) Technical and Economic Aspects of Load Following with Nuclear Power Plants, OECD/NEA June 2011
2) System effects of nuclear energy and renewables in low-carbon electricity systems, OECD/NEA News No. 7164 2012/2013
3) Load-following with nuclear power plants, OECD/NEA News 2011- No. 29.2

Grid level system costs

Table 2: **Grid-level system costs in selected OECD/NEA countries** (USD/MWh)

Finland												
Technology	**Nuclear**		**Coal**		**Gas**		**Onshore wind**		**Offshore wind**		**Solar**	
Penetration level	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**
Back-up costs (adequacy)	0.00	0.00	0.06	0.06	0.00	0.00	8.05	9.70	9.68	10.67	21.40	22.04
Balancing costs	0.47	0.30	0.00	0.00	0.00	0.00	2.70	5.30	2.70	5.30	2.70	5.30
Grid connection	1.90	1.90	1.04	1.04	0.56	0.56	6.84	6.84	18.86	18.86	22.02	22.02
Grid reinforcement and extension	0.00	0.00	0.00	0.00	0.00	0.00	0.20	1.72	0.12	1.04	0.56	4.87
Total grid-level system costs	**2.37**	**2.20**	**1.10**	**1.10**	**0.56**	**0.56**	**17.79**	**23.56**	**31.36**	**35.87**	**46.67**	**54.22**