Representation of uncertainty in market models for renewable power systems

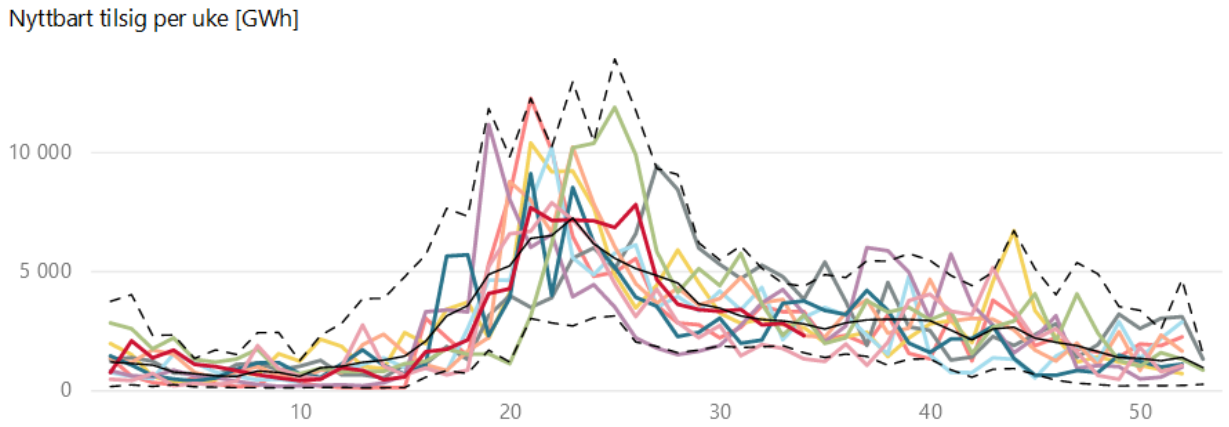
Mari Haugen[1,2], Hossein Farahmand[1], Stefan Jaehnert[2], Stein-Erik Fleten[3]

[1]Department of Electric Power Engineering, NTNU
[2]Energy Systems, SINTEF Energy Research
[3]Department of Industrial Economics and Technology Management, NTNU

Hydropower Scheduling Conference 12th September 2022

Motivation

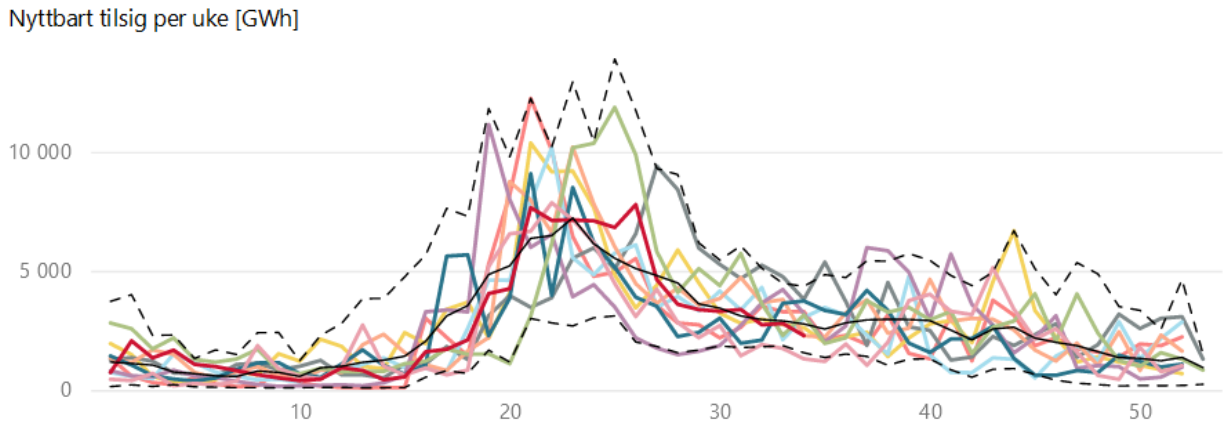
- Operational planning of hydropower



From NVE

Motivation

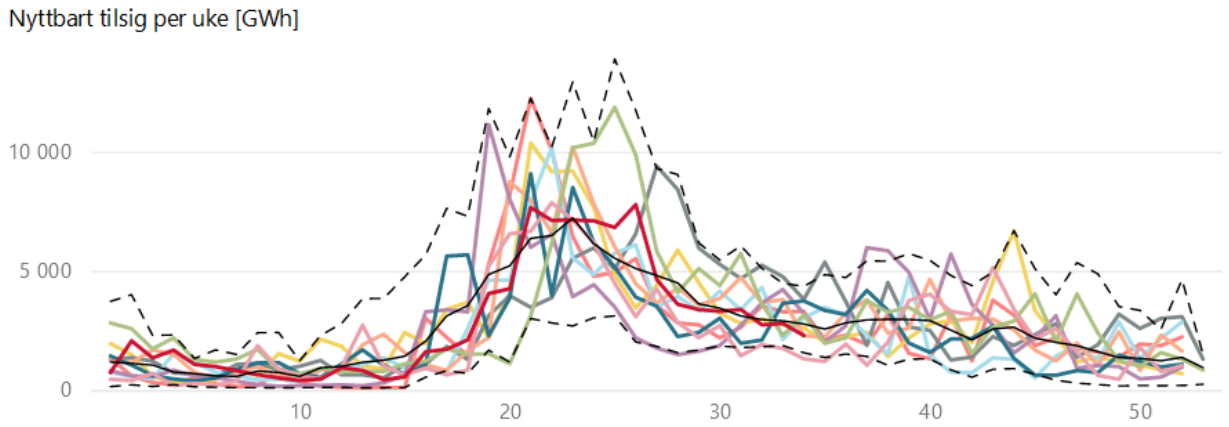
- Operational planning of hydropower
- The future is uncertain!



From NVE

Motivation

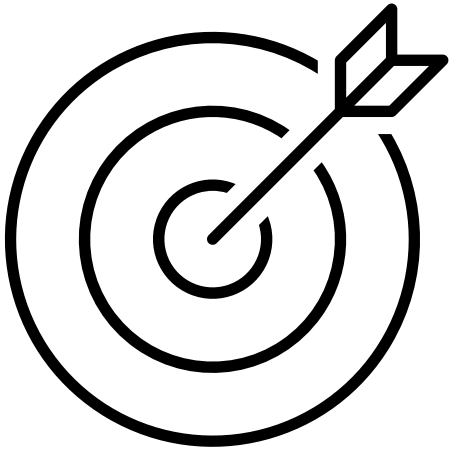
- Operational planning of hydropower
- The future is uncertain!
- Increased need for decision support tools and increased levels of uncertainty
  - VRE integration
  - Market liberalization
  - Climate change
  - Changing regulations
  - Technology development
- Uncertainty is often overlooked or simplified in models



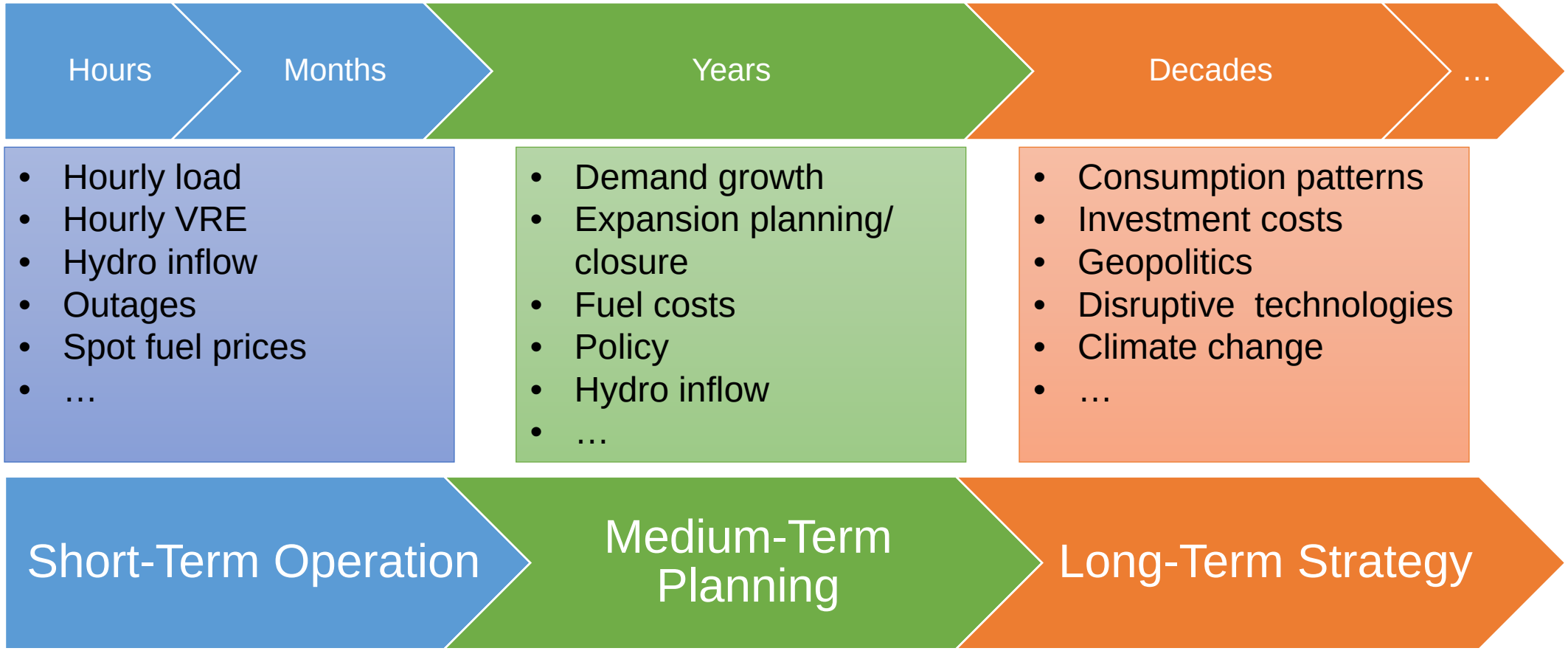
From NVE

Goal of the review

- Review the representation of uncertainty in applied power market models
  - Types
  - Timescales
  - Methods
- Overview of methods:
  - Stochastic optimization
  - Scenario generation and reduction
- Identifying critical uncertainties and suitable methods



Timescale of uncertainty



Based on Velasquez et al. (2016)

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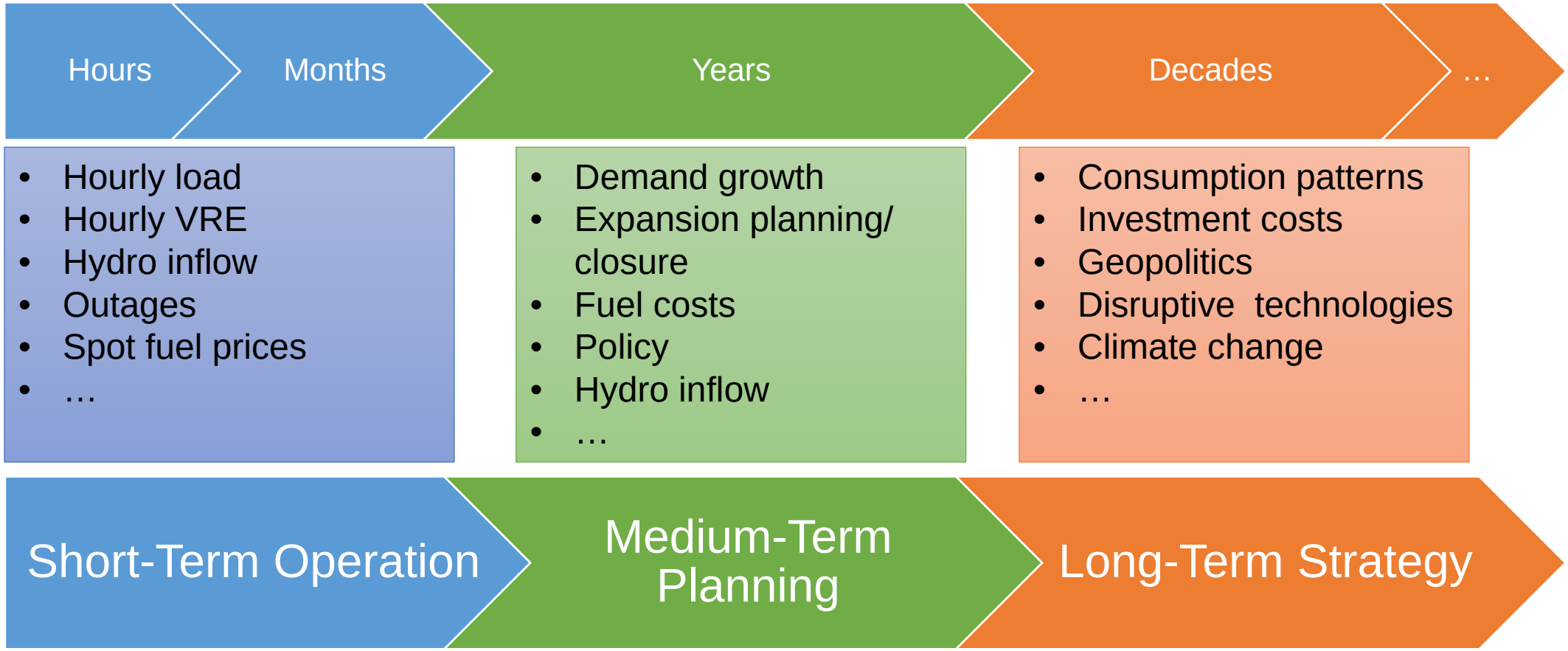

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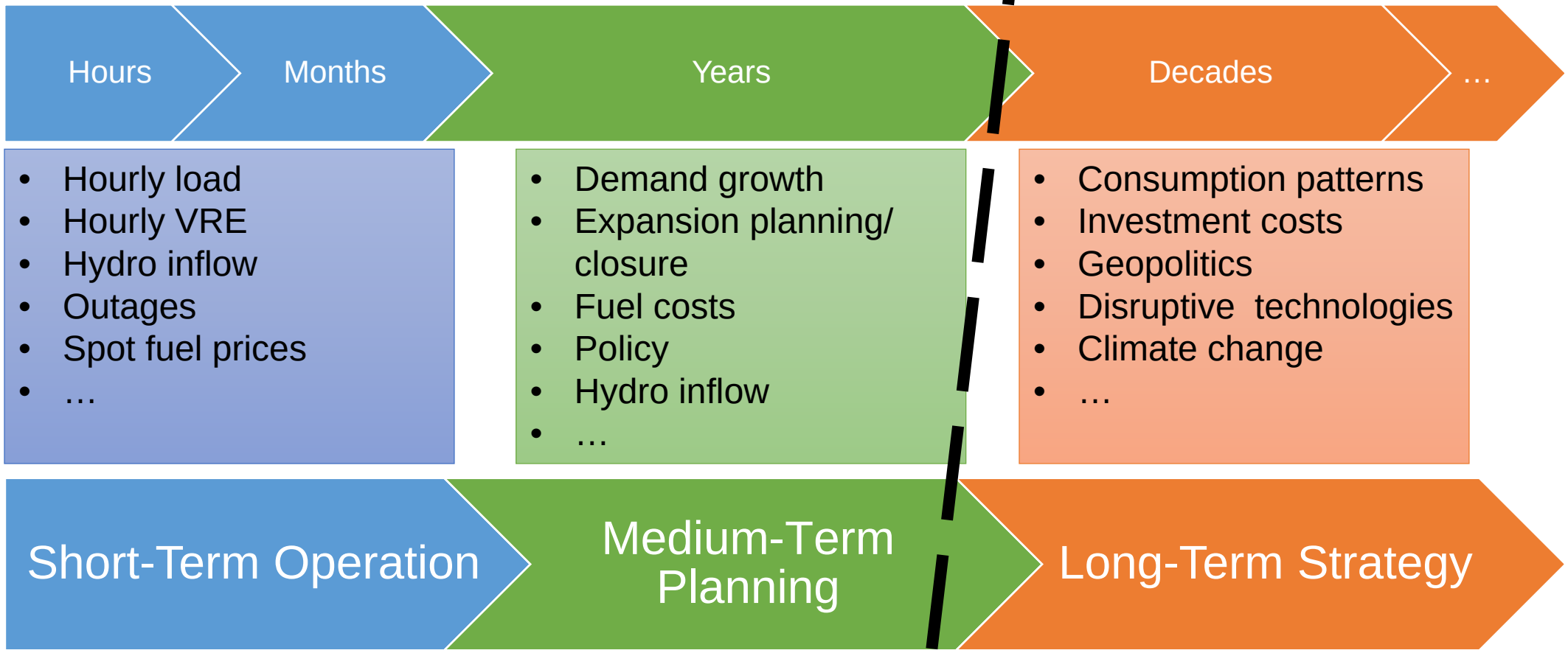
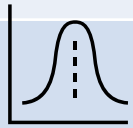


Based on Velasquez et al. (2016)

Structure of uncertainty

Uncertainty			
	«Known»	«Unknown»	«Unknowable»
Examples	• Demand • Weather-related power production	• Outages/availability • Fuel prices/shortage • Extreme weather	• Black swans • Terror and war • Natural disasters
Appropriate representation	• Probabilistic representation • Stochastic process 	• Bounded sets/Intervals • Fuzzy sets	• Scenarios
Suitable method	• Stochastic programming	• Robust optimization • Fuzzy programming	??

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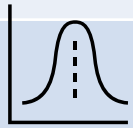
Appropriate representation	• Probabilistic representation • Stochastic process 	• Bounded sets/Intervals • Fuzzy sets	• Scenarios
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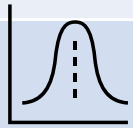
Appropriate representation	• Probabilistic representation • Stochastic process 	• Bounded sets/Intervals • Fuzzy sets	• Scenarios
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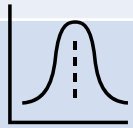
Appropriate representation	• Probabilistic representation • Stochastic process 	• Bounded sets/Intervals • Fuzzy sets	• Scenarios
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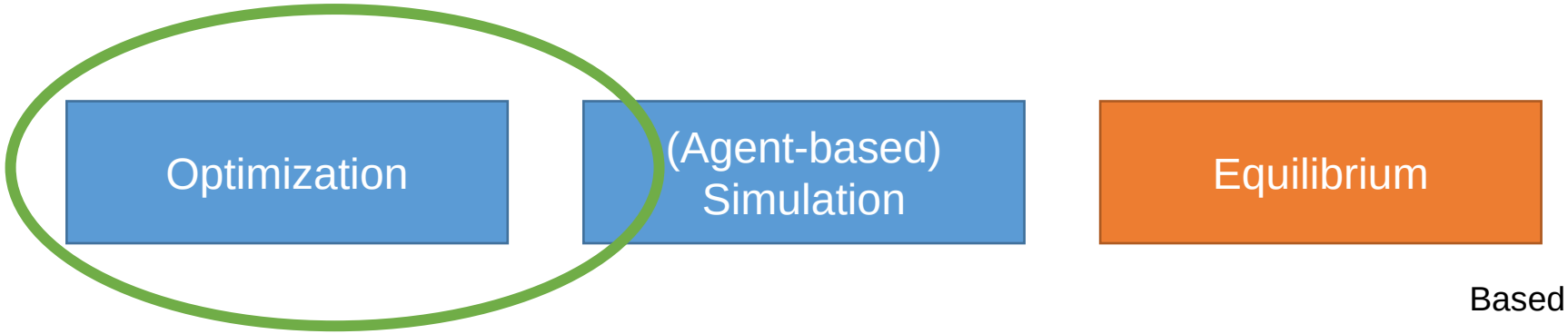
Power market models



Based on Ventosa et al. (2005)

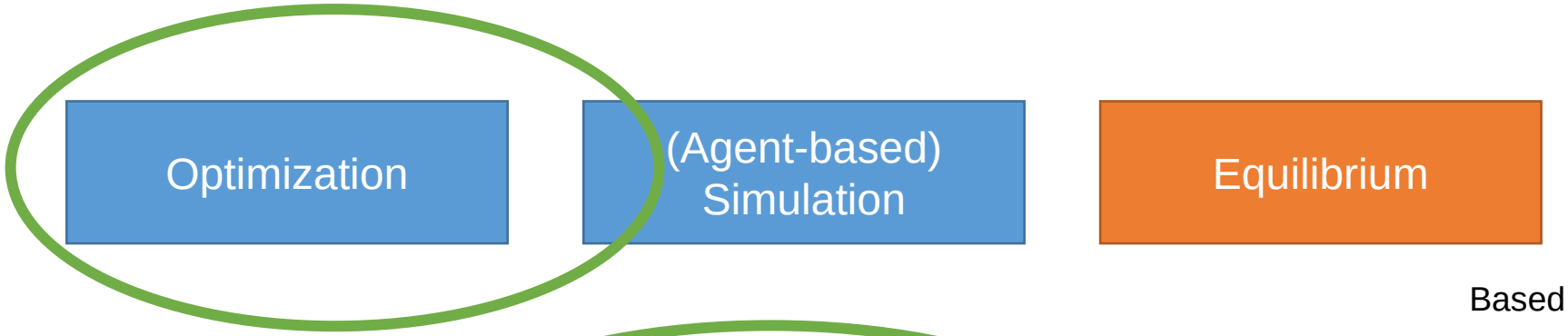
Power market models

Based on Ventosa et al. (2005)

Optimization

- Deterministic
- Multi-deterministic
  - Scenario analysis
  - Monte Carlo
- Stochastic
  - Stochastic programming
  - Chance-constrained programming
  - Robust programming
  - Distributionally robust optimization
  - Interval programming
  - Fuzzy programming

Power market models



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Fundamental models

- Physical description
- Explaining complex relationships
- Suitable for analysing future systems

Power market models

Optimization

(Agent-based) Simulation

Equilibrium

Based on Ventosa et al. (2005)

Optimization

- Deterministic
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Applications

- Forecast power prices
- Unit commitment and dispatch
- Operational decisions (scheduling)
- Hydrothermal coordination
- Power market analysis
- Analyse market design
- Expansion planning
- ….

Name	Reference	Time horizon	Problem solved	Uncertainty					Problem formulation	Solution method
				Demand	Hydro Inflow	VRES	Fuel prices	Outages		
EMPS	Wolfgang et al (2009)	Long	Hydrothermal coordination	X	X	X	(X)		multi-stage stochastic linear programming problem	SDP
FanSi	Helset et al. (2007)	Long	Hydrothermal coordination	X	X	X	(X)		two-stage stochastic linear programming problem	Benders decomposition and rolling horizon
NEWAVE	Maceria et al. (2008).	Long	Hydrothermal coordination		X				multi-stage stochastic linear programming problem	SDDP
WILMAR	Meibom et al. (2011)	Short	Unit commitment and dispatch	X		X		X	stochastic mixed integer linear optimization problem	Rolling horizon
E2M2	Sun et al. (2008) / Swider and Weber (2007)	Long	Unit commitment and generation expansion planning			X		X	stochastic mixed integer linear optimization problem	Representative days, recombining three
stELMOD	Abrell and Kunz (2015)	Short	Unit commitment and dispatch			X			stochastic mixed integer linear optimization problem	Rolling horizon
VALORAGUA	Baptista and Tavares (1987)	Long	Hydrothermal coordination	X	X			X	multi-stage stochastic linear programming problem	SDP
Based on URBS	Heitmann and Hamacher (2009)	Medium	Plan generation mix			X	X		two-stage stochastic linear programming problem	Representative hours/days
SiSTEM	Mathieu et al. (2017)	Short	Unit commitment and optimal bidding in sequential markets	X		X		X	Optimization and agent-based simulation	Simulation (combining optimization and simulation)
Antares	Doquet et al. (2008), Alimou et al. (2020)	Long	System adequacy, unit commitment and dispatch	X	X	X		X	(Mixed integer) linear optimization problem	Monte-Carlo simulation and heuristics

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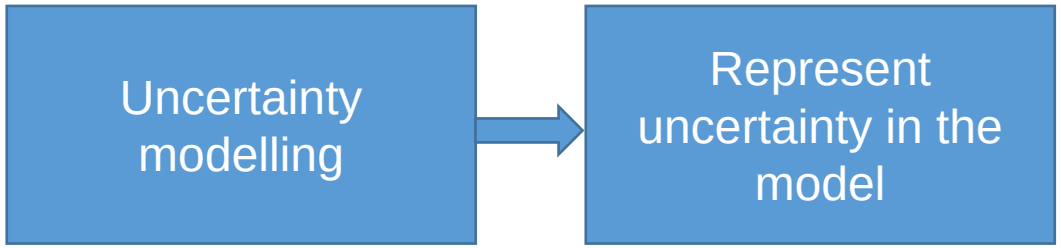
Summary

Uncertainty modelling

- Challenges:
  - Describing the uncertainties

Summary



- Challenges:
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  - Making good scenarios

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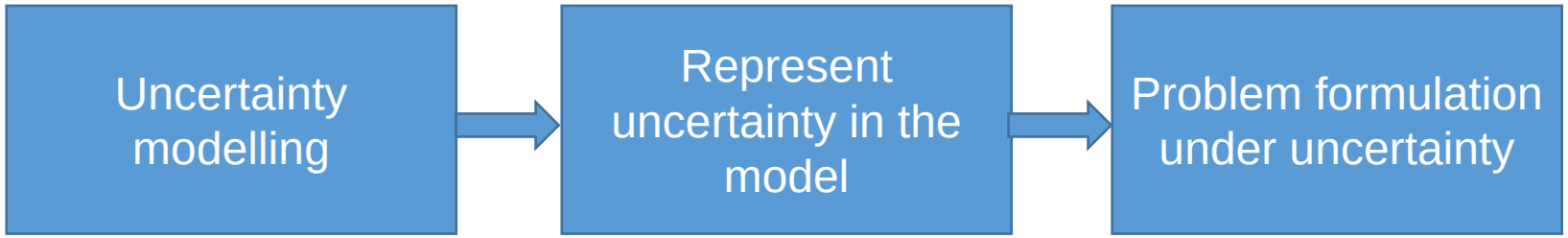

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  - Transparency ←→ Complexity

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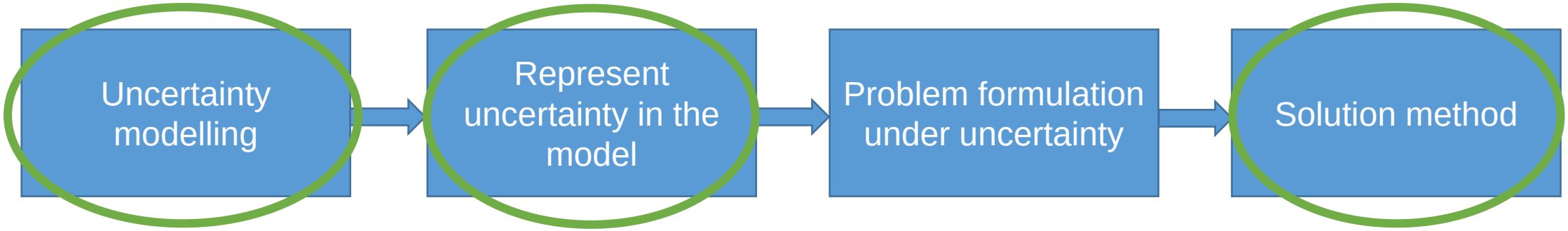

- Challenges:
  - Describing the uncertainties
  - Making good scenarios
  - Transparency ←→ Complexity
  - Computation time

Conclusions

- Stochastic optimization is the best choice!
- Wider range of uncertainties instead of more detail

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- Stochastic optimization is the best choice!
- Wider range of uncertainties instead of more detail
- Identified research gap:

Models representing multiple dimensions of uncertainty,
and that can be solved on a real-size system in a reasonable time

Main references

- D. Möst and D. Keles, “A survey of stochastic modelling approaches for liberalised electricity markets,” *Eur. J. Oper. Res.*, vol. 207, no. 2, pp. 543–556, Dec. 2010
- A. Zakaria, F. B. Ismail, M. S. H. Lipu, and M. A. Hannan, “Uncertainty models for stochastic optimization in renewable energy applications,” *Renew. Energy*, vol. 145, pp. 1543–1571, Jan. 2020
- B. C. R. Fernandez, F. Careri, K. Kavvadias, G. I. Hidalgo, A. Zucker, and E. Peteves, “Systematic mapping of power system models: Expert survey,” *JRC Publications Repository*, Dec. 04, 2017
- C. Velasquez, D. Watts, H. Rudnick, and C. Bustos, “A Framework for Transmission Expansion Planning: A Complex Problem Clouded by Uncertainty,” *IEEE Power Energy Mag.*, vol. 14, no. 4, pp. 20–29, Jul. 2016
- M. Ventosa, Á. Baíllo, A. Ramos, and M. Rivier, “Electricity market modeling trends,” *Energy Policy*, vol. 33, no. 7, pp. 897–913, May 2005
- L. A. Roald, D. Pozo, A. Papavasiliou, D. K. Molzahn, J. Kazempour, and A. Conejo, “Power Systems Optimization under Uncertainty: A Review of Methods and Applications,” *Electric Power Systems Research*, 2022
- I. J. Scott, P. M. S. Carvalho, A. Botterud, and C. A. Silva, “Long-term uncertainties in generation expansion planning: Implications for electricity market modelling and policy,” *Energy*, vol. 227, 2021
- J. Haas *et al.*, “Challenges and trends of energy storage expansion planning for flexibility provision in low-carbon power systems – a review,” *Renew. Sustain. Energy Rev.*, vol. 80, pp. 603–619, Dec. 2017