Dynamic quality regulation of the electricity grid

Exploring effects of path dependencies in engineered systems

Jonathan Barth[a], Klaus Eisenack[b], Ulrike Feudel[a], Jasper Meya[a,b]

[a]Theoretical Physics and Complex Systems, Universität Oldenburg

[b]Resource Economics Group, Humboldt-Universität zu Berlin

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Motivation – General

- **High macroeconomic costs** associated with electricity shortages (Bliem, 2005)

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- **High macroeconomic costs** associated with electricity shortages (Bliem, 2005)
- **Dynamics** of quality investments are not well understood
  - a) Mostly **static** modelling approaches

Study	Regulation type	Model type	Investment type
El-Hodiri and Takayama (1981)	Cost based	Dynamic continuous	Quantity
Besanko et al. (1987)	Quality only	Dynamic continuous	Quality
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Niho and Musacchio (1983)	Cost based	Dynamic continuous	Quantity
Biglaiser and Riordan (2000)	Incentive and cost based	Dynamic continuous	Quantity
Fellows (2015)	Cost based	Dynamic continuous	Quantity
Vogelsang and Finsinger (1979)	Incentive	Dynamic discrete	Quantity
Sappington (1980)	Incentive	Dynamic discrete	Quantity
Currier (2007)	Incentive	Dynamic discrete	Quantity and quality
Fraja (2008)	Incentive	Dynamic discrete	Quantity and quality
Auray et al. (2011)	Quality only	Dynamic discrete	Quality
Schill et al. (2015)	Incentive and cost based	Dynamic discrete	Quantity
Schober and Weber (2015)	Incentive	Dynamic discrete	Quantity
Weber et al. (2010)	Incentive	probabilistic	Quality
Spence (1975)	Cost based	Static	Quantity and quality
Sheshinski (1976)	Incentive	Static	Quantity and quality
Lewis and Sappington (1991)	Quality only	Static	Quality
Tangerås (2009)	Incentive	Static	Quantity and quality
Averch and Johnson (1962)	Cost based	Static	Quantity

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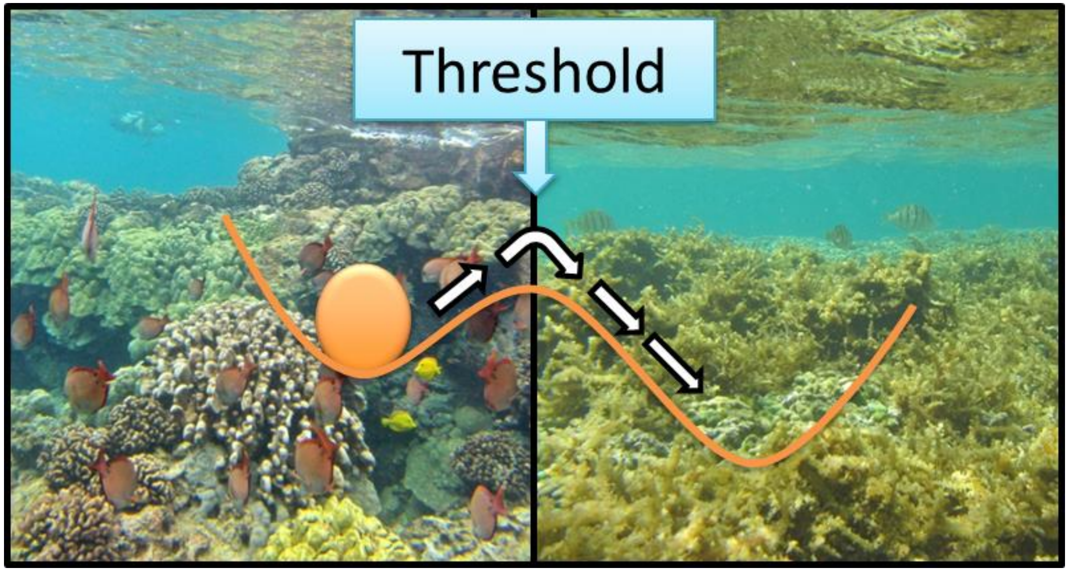
  - b) **Path dependencies** are blind spot



Source: oceantippingpoints.org

Conditions for path dependencies in environmental economics:

- Convex economies with increasing returns (Arthur, 1989)
- Positive control-state interactions (Wirl and Feichtlinger, 2005)
- Growth rates above the discount rate (Wirl and Feichtliner, 2005)

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Motivation - Research Question

How do path dependencies influence the investment behavior in quality of the energy grid by a regulated monopolist?

Structure

Part I

- Modelling Quality dynamics
- Theoretical Derivation of path dependencies

Part II

- Application to a conceptual model
- Investment behaviour in the face of path dependencies

Discussion

Model I: Dynamic modelling of quality dynamics

Quality dynamics

(Auray, 2011)

$$\dot{q} = \frac{v}{\bar{\mathrm{x}}} - \delta^Q q$$

$$\text{with } \bar{\mathrm{x}} = const.$$

$v/\bar{x}$: Maintenance and replacement investments

$\bar{x}$: Stock of capital (amount; installed capacity)

q: Quality of existing capital stock

Sources:

Model I: Investment & dynamic optimization

Objective function

$$\max \int_0^\infty [p(q) - O(q) - C(v)]\, e^{-\rho t}\, dt$$

$$\text{with } \dot{q} = v - \delta^Q(q)\, q$$

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p: price

v: Maintenance and replacement investments

q: Quality of existing capital stock

δ^Q: Depreciation rate of quality

O, C: operating and capital costs

Result I – Proposition

Path dependencies may occur if depreciation rates are not constant but dependent on quality and either of the following holds

- $\delta_q^Q < 0$ and either O_{qq} or p_{qq} are not constant
- $\delta_q^Q < 0$ and $\delta_{qq}^Q > 0$
- $\delta_q^Q > 0$ and $\delta_{qq}^Q < 0$

Model II:
Simple application to energy grids & regulation

Assumption: capital quality ~ supply quality

⇒ Negative Feedbacks through blackouts
(Carrearas et al., 2003; Corwin and Miles, 1978)

⇒ Nonlinear endogenous depreciation with
$\delta_q^Q < 0$ and $\delta_{qq}^Q > 0$:

$$\delta^Q(q) = \bar{\delta}\left(\frac{(1-s)(q^2 - 2q\, q_{max})}{q_{max}^2} + 1\right)$$

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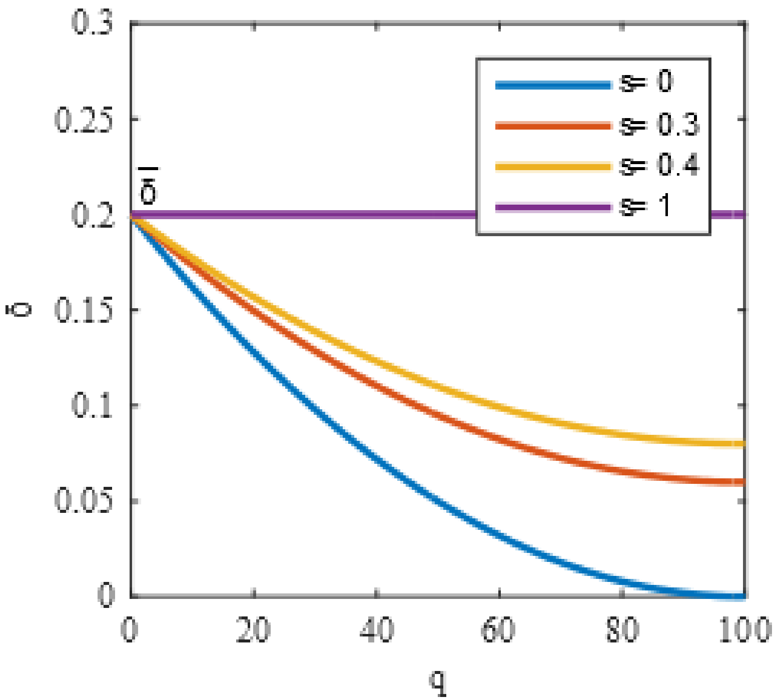
q: Quality of existing capital stock
δ^Q: Depreciation rate of quality
s: Degree of nonlinearity and inclination

Model II:
Simple application to energy grids & regulation

$$\delta^Q(q) = \bar{\delta}\left(\frac{(1-s)(q^2 - 2q\, q_{max})}{q_{max}^2} + 1\right)$$



Depreciation rates for different values of s with $\bar{\delta} = 0.2, q_{max} = 100$

Model II:
Simple application to energy grids & regulation

Dynamic price cap adjustment

$$p(t) \leq p_R(t) = \alpha O(q) + \beta C(v) + \gamma\, q$$

Model II: Simple application to energy grids & regulation

Inverse demand: $p(t) = a \frac{q}{\bar{x}+1}$

Utility: $U(t) = a\, q \ln(\bar{x} + 1)$

Operating costs: $O(q) = o\, q(t)\, \bar{x}$

Capital costs: $C(v) = c\, v^2$

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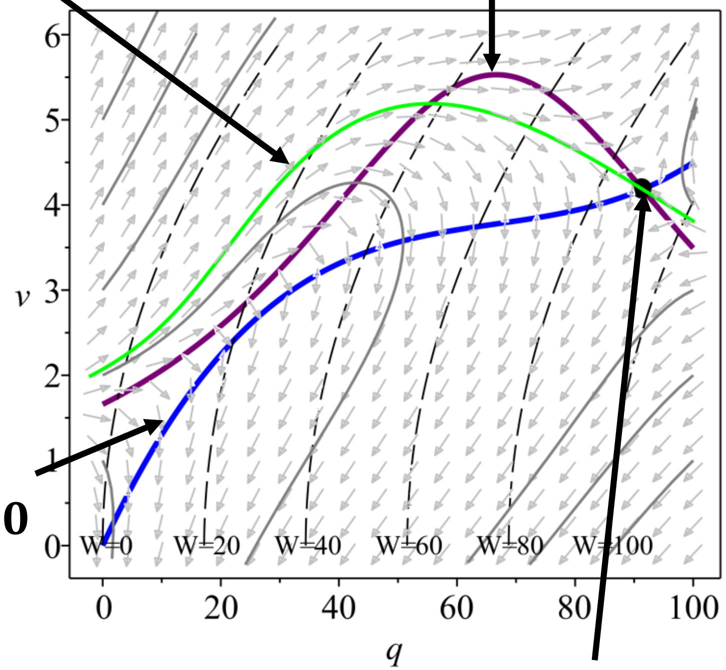
a: Willingness to pay for quality

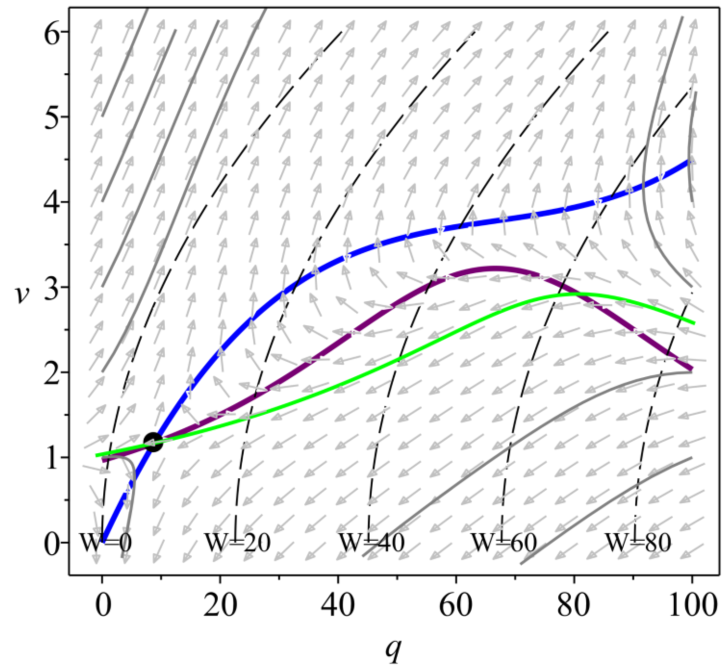
v: investments in maintenance

q: Stock of quality

Results II: Single steady states

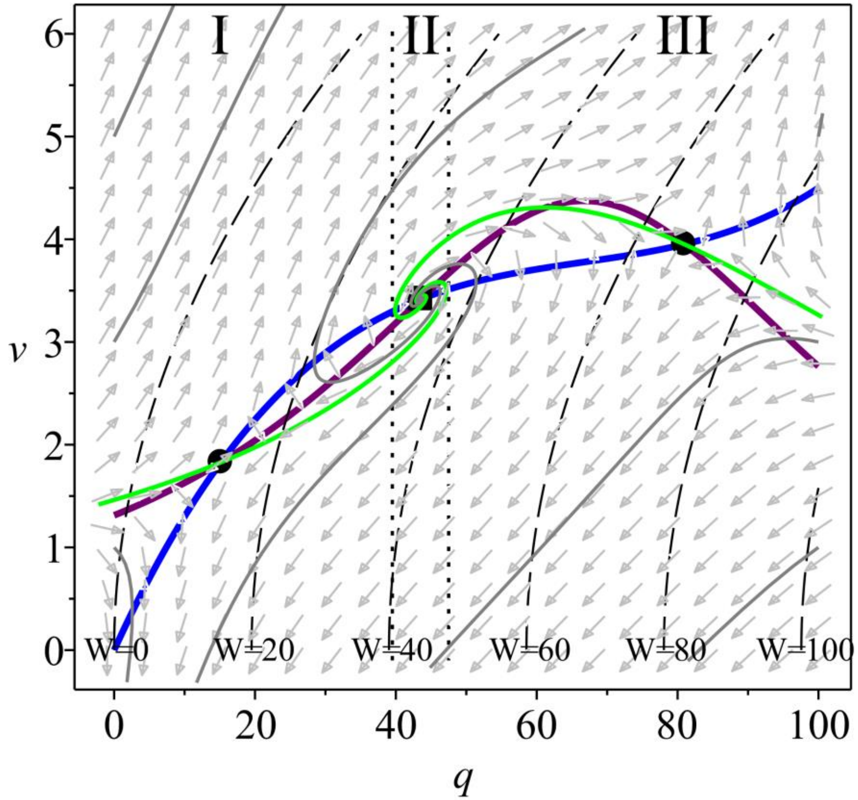


Phase space plot – social planer
with $\boldsymbol{a} = \mathbf{2.4}$, $\bar{\delta} = 0.15, s = 0.3, q_{max} = 100$



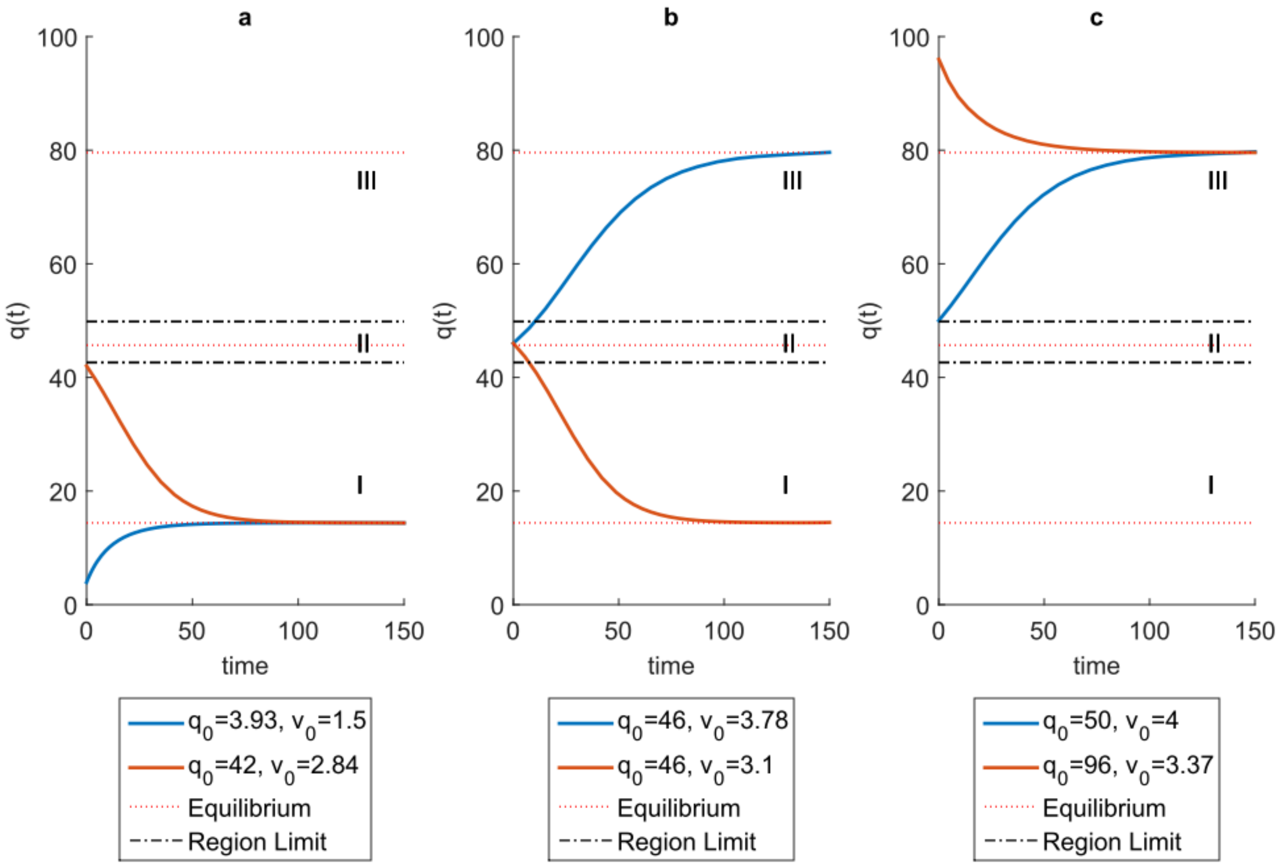
Phase space plot – social planer
with $\boldsymbol{a} = \mathbf{2.0}$, $\bar{\delta} = 0.15, s = 0.3, q_{max} = 100$

Results II: Multiple steady states & path dependencies



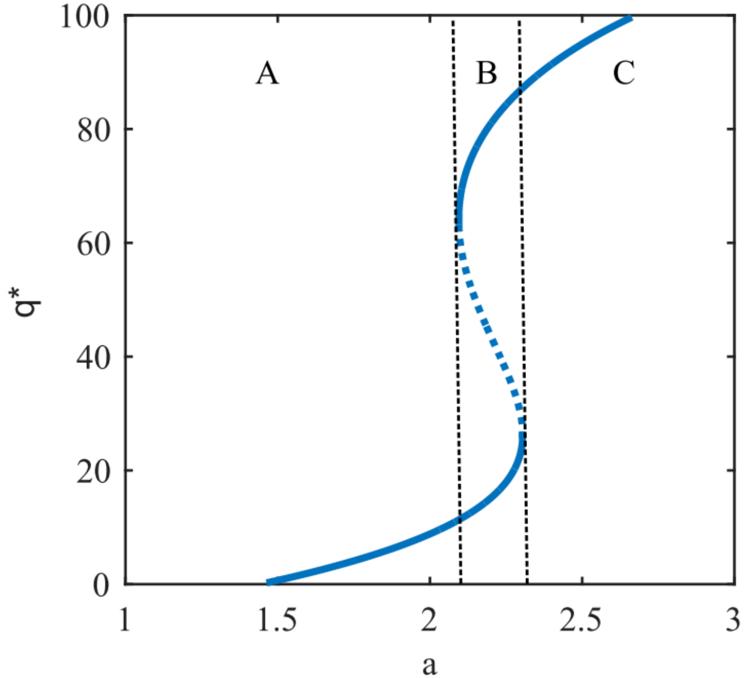
Phase space plot – social planer
with $\boldsymbol{a} = \mathbf{2.2}$, $\bar{\delta} = 0.15, s = 0.3, q_{max} = 100$

Results II: Multiple steady states & path dependencies

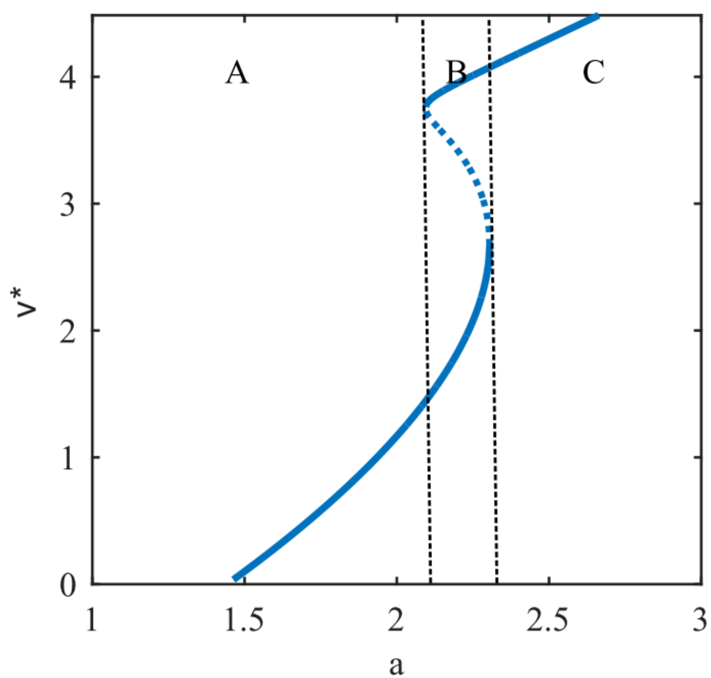


Phase space plot – social planer
with **a=2.2**, $\bar{\delta} = 0.15, s = 0.3, q_{max} = 100$

Results II: Stability analysis



Bifurcation diagramm for q^* with respect to a



Bifurcation diagramm for v^* with respect to a

Discussion and open questions

In progress

- Comparing the optimality of different regulatory regimes
- Analysing conditions for binding and non-binding regulation in a dynamic setting

Open for elaboration

- Variation of assumptions
- Transfer of approach to other technical systems
- Empirical proof for endogenous quality depreciation
- Calibration of the model

Selected references

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Thank you and stay in touch

Jonathan Barth

Universität Oldenburg

Theoretical Physics and Complex Systems

M: Jonathan.barth@uni-oldenburg.de

T: @JonathanB4RTH