16th IAEE European Conference, Ljubljana, August 28th 2019

AC vs. DC – The “Current” Battle of the Currents

An Applied System Good- and Lock-In Economics Approach

Florian Weiß, Raluca Dumitrescu, Daniel Philipp, Christian von Hirschhausen and Friedrich Wicke
Berlin University of Technology, Workgroup for Economic and Infrastructure Policy (WIP)

Agenda

1) Introduction and Motivation
2) Basic Theory and Organizational Model
3) Application of the Organizational Model
4) Results and Conclusion

Introduction and Motivation

Why is AC/DC Research interesting?

1. **Theoretically**

   Special case study for applied **historical network economics** → QWERTY-economics

   - Dynamicity through impossibility of complete absence of DC within the *system good* of energy supply

2. **Practically**

   Real improvements of efficiency all over the value chain and fundamental reduction of conversion losses

   - Several disadvantages as results of incompatibility within the system

The Background

- Positive: A lot of technical literature is already existing, presenting a lot of advantages of DC over AC
- Worth continuing: It lacks of economic specification, in which context these potentials can be optimally exploited → this is, where we start!

What We Are Talking About

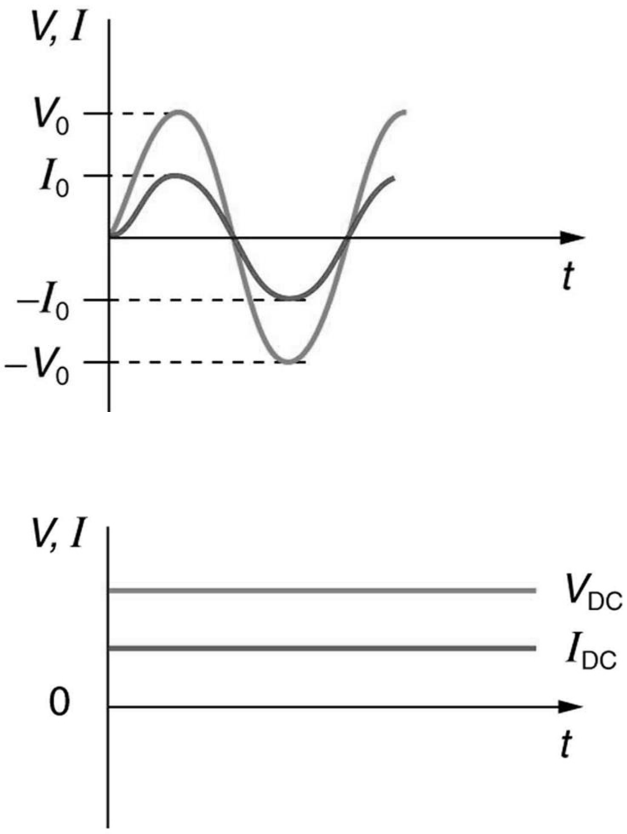


Figure 1: AC and DC two dimensional

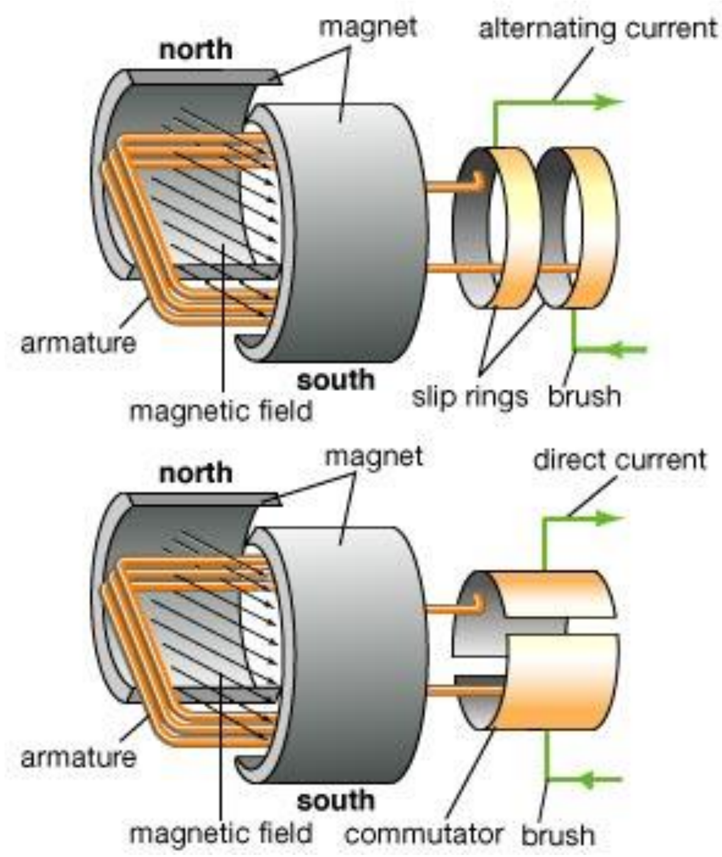


Figure 2: Functionality of AC and DC motors (Source: Merriam-Webster Inc. 2006)

Agenda

1) Introduction and Motivation
2) **Basic Theory and Organizational Model**
3) Application of the Organizational Model
4) Results and Conclusion

Some Basic Theory

Network Economics

1. Direct network effects
    - ○ Complex good *energy supply and provision* is subject to the principles of economics of scale
2. Indirect network effects
    - ○ Provision of energy **is** a complex good

$$U^x = \begin{cases} n(1-x) - p & \text{if he or she subscribes to the phone system} \\ 0 & \text{if he or she does not subscribe.} \end{cases}$$

Decisions Within the System by Costumers and Suppliers (Manufacturers Included) Depend on the Following:

1. <u>Question of the technology adoption:</u> “What technology to choose with which characteristics and how many consumers are expected?”,
2. <u>Issue of product selection:</u> “Which factors are relevant for the consumers choice among the existing (and rivalery) options?”,
3. <u>Anticipation in terms of compatibility:</u> “Which firms will seek compatibility, and which not?”

Network Externalities

- In case that **both technologies are incompatible** to each other and consumers do not decide accordingly to their utility function, the maximum possible generated utility of this not optimally chosen good is decreased by an amount δ.
- In case good *a* is optimal for consumer a, the utility is $U_a(a)$. If it is not optimal, the highest possible generated utility $U_a(a) - \delta$.

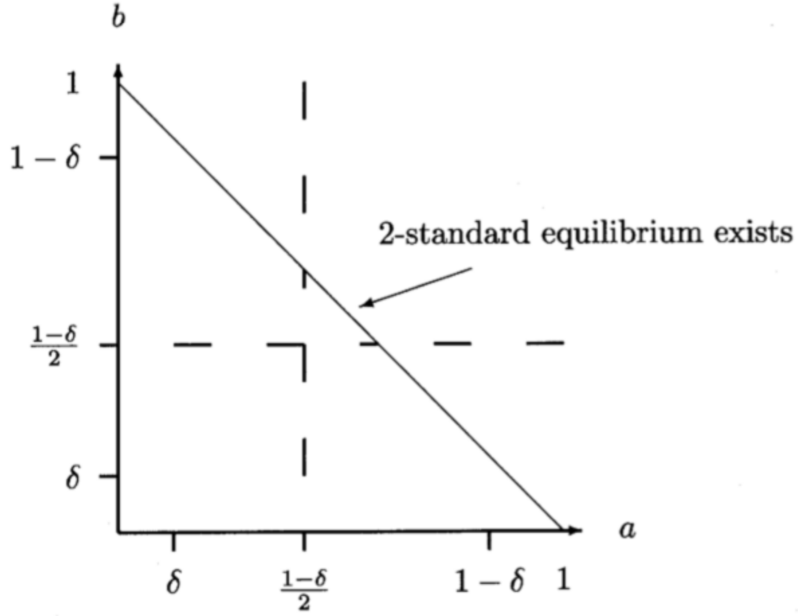


Figure 3: Two-standard (incompatibitlity) equilibrium (Source: Shy (1995))

Lock-In Effects and Complex Good Principles

Following Factors Determine the "Grade of Lock-In"

1. Technological Dependencies
2. Scale effects
3. Irreversibility of Investments

Complex Goods

A complex "good" consists of different services and goods:

- Institutions (f. e. regulation)
- Players with roles and relationships
- Technical system (Depending on time!)

Positive Correlation

Network effects

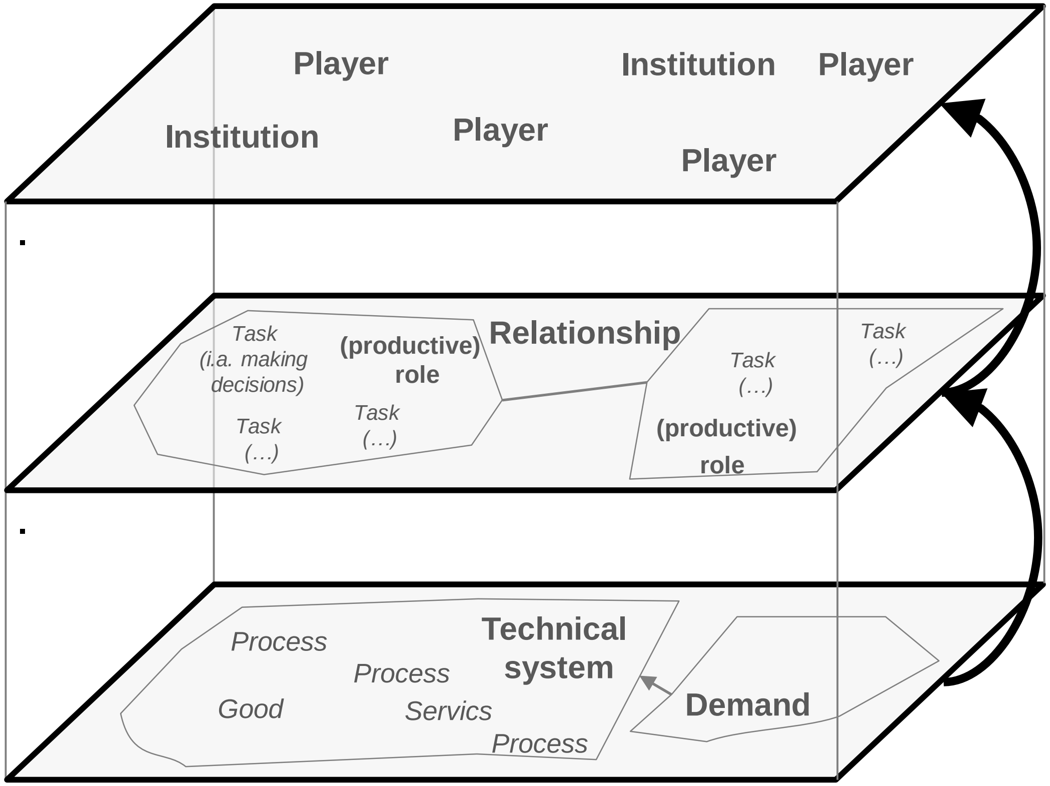
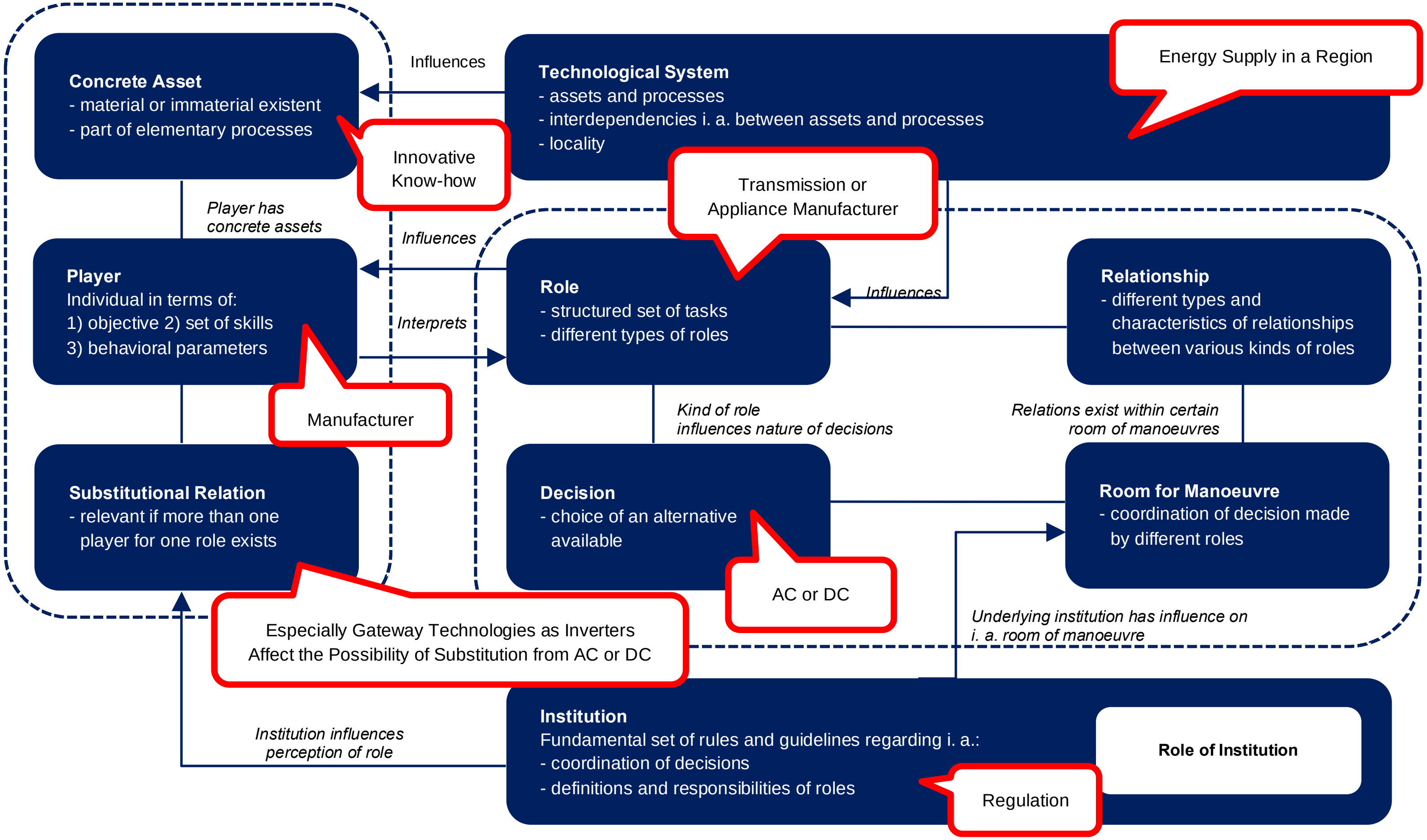


Figure 4: The three layers of a system good environment

(Based on Beckers et al. (2012))

Complex Goods: An Overview



Concrete Asset
- material or immaterial existent
- part of elementary processes

Technological System
- assets and processes
- interdependencies i. a. between assets and processes
- locality

Player
Individual in terms of:
1) objective 2) set of skills
3) behavioral parameters

Role
- structured set of tasks
- different types of roles

Relationship
- different types and characteristics of relationships between various kinds of roles

Substitutional Relation
- relevant if more than one player for one role exists

Decision
- choice of an alternative available

Room for Manoeuvre
- coordination of decision made by different roles

Institution
Fundamental set of rules and guidelines regarding i. a.:
- coordination of decisions
- definitions and responsibilities of roles

Role of Institution

Figure 5: Elements of a System Good Based Analysis and Important Links

(Based on Beckers et al. (2012))

The Organizational Model

Relevant Criteria to be Destinguished

1. Two different systems with respectively differing levels of technological developments are compared. These levels depend on the related point of **time.**
2. Already **existing infrastructure** could be present to both considered points of time.

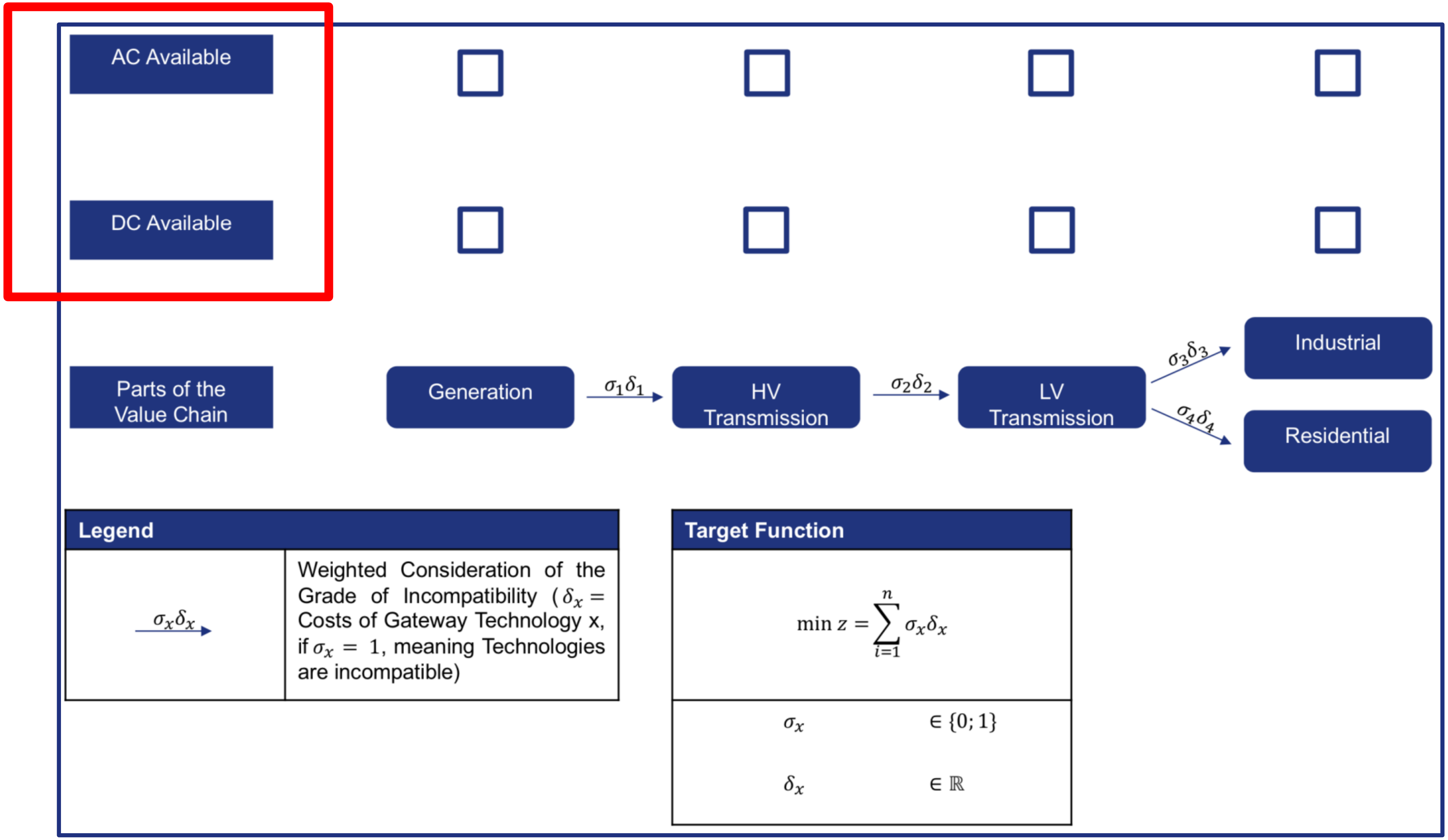
Existing Infrastructure ↓

Time →

	Without Lock-In	**With Lock-In**
t_{-1} (≈ 1900)	AC	-
t_0 (≈ 2020)	DC	Approach 1 (Bottom-up) Approach 2 (Top-down)

Table 1: Four cases to be considered (Authors design)

The Organizational Model



AC Available ☐ ☐ ☐ ☐

DC Available ☐ ☐ ☐ ☐

Parts of the Value Chain

Generation $\xrightarrow{\sigma_1\delta_1}$ HV Transmission $\xrightarrow{\sigma_2\delta_2}$ LV Transmission $\xrightarrow{\sigma_3\delta_3}$ Industrial

LV Transmission $\xrightarrow{\sigma_4\delta_4}$ Residential

Legend	
$\xrightarrow{\sigma_x\delta_x}$	Weighted Consideration of the Grade of Incompatibility ($\delta_x =$ Costs of Gateway Technology x, if $\sigma_x = 1$, meaning Technologies are incompatible)

Target Function

$$\min z = \sum_{i=1}^{n} \sigma_x \delta_x$$

σ_x	$\in \{0; 1\}$
δ_x	$\in \mathbb{R}$

Figure 6: The organizational model (Authors design)

Gateway Technologies and Compatibility

- If it comes to illustrating the evolution of the discussed topic, gateway technologies are of central importance, since the existence of converters and inverters are enabling the transformation from AC to DC and vice versa. → **Enabling compatibility**
- On previous slides, it was observed that the **design and implementation of interfaces are of crucial importance** (with target function of minimizing system costs)

Gateway Technologies and Network Externalities

Generally speaking, δ represents the barrier, that has to be overcome by a certain gateway technology. Variable ε characterizes the potential level of incompatibility, which possibly could be turned into compatibility by a certain gateway technology.

If:

1. $\delta \leq \varepsilon$, the gateway technology is able to establish compatibility.
2. $\delta > \varepsilon$, establishing compatibility is not possible and the originally incompatible technologies remain incompatible.

Agenda

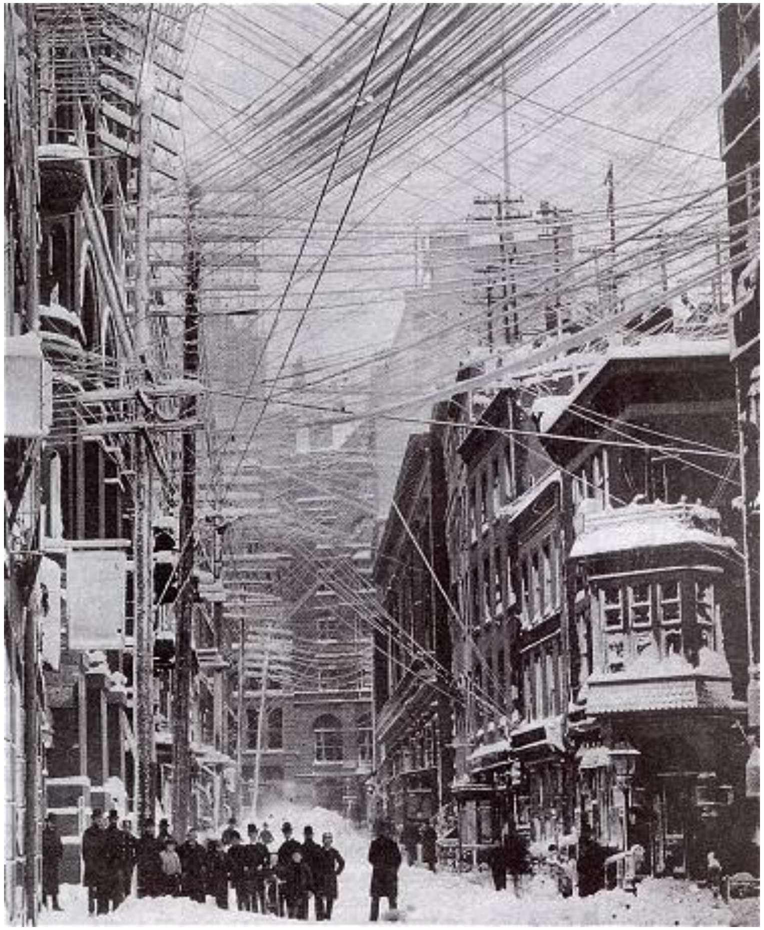
1) Introduction and Motivation
2) Basic Theory and Organizational Model
3) **Application of the Organizational Model**
4) Results and Conclusion

Application of the Organizational Model: t_{-1}

- A[illegible]vention of DC by Thomas Edison arou[illegible]80s, and its rapid diffusion, AC network[illegible]en over in the period of late 1880s and [illegible] driven by the ease of AC in transporting [illegible] over longer distances and the capac[illegible]signing complex networks, thus lead[illegible]asive network effects (Hughes 1993).

- Battle ends with investor Westingh[illegible]g a decisive tender for the Int[illegible] Exposition in Chicago in 1993,

Not enough time for this



http://historyimages.com/Vintage-NY/Blizzard-88.html

New York, before 1890‘s destruction by heavy blizzards.

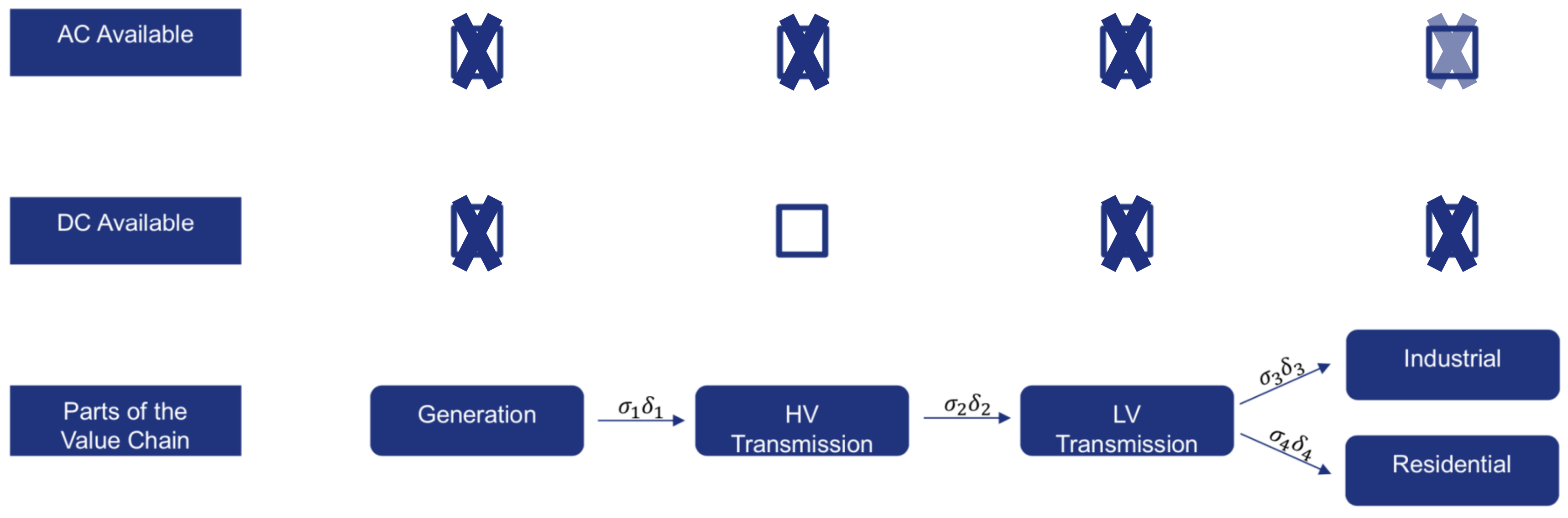
Application of the Organizational Model: t_0

Alternating Curr[illegible]t Current

- Since the electri[illegible] Europe and the USA the historic battle of the currents began, when Alterna[illegible]nt (AC) defeated Direct Current (DC), due to lower costs concerning the tra[illegible]f electricity.
- Technological advantages o[illegible]red to DC in the 19th century were the crucial factors, that – for the time bein[illegible] win the battle for lock-in (Hughes 1993). Generally, DC has been forced bac[illegible]he inside of lithium accumulators and LED lights, but due to progress concern[illegible]C transmission, the original battle of the currents has been restarted
    - **…but with redistributed chances to win.**

Not enough time for this

Application of the Organizational Model: t_{-1}



AC Available	☒	☒	☒	☒
DC Available	☒	☐	☒	☒
Parts of the Value Chain	Generation	HV Transmission	LV Transmission	Industrial Residential

Legend	
$\xrightarrow{\sigma_x\delta_x}$	Weighted Consideration of the Grade of Incompatibility ($\delta_x =$ Costs of Gateway Technology x, if $\sigma_x = 1$, meaning Technologies are incompatible)

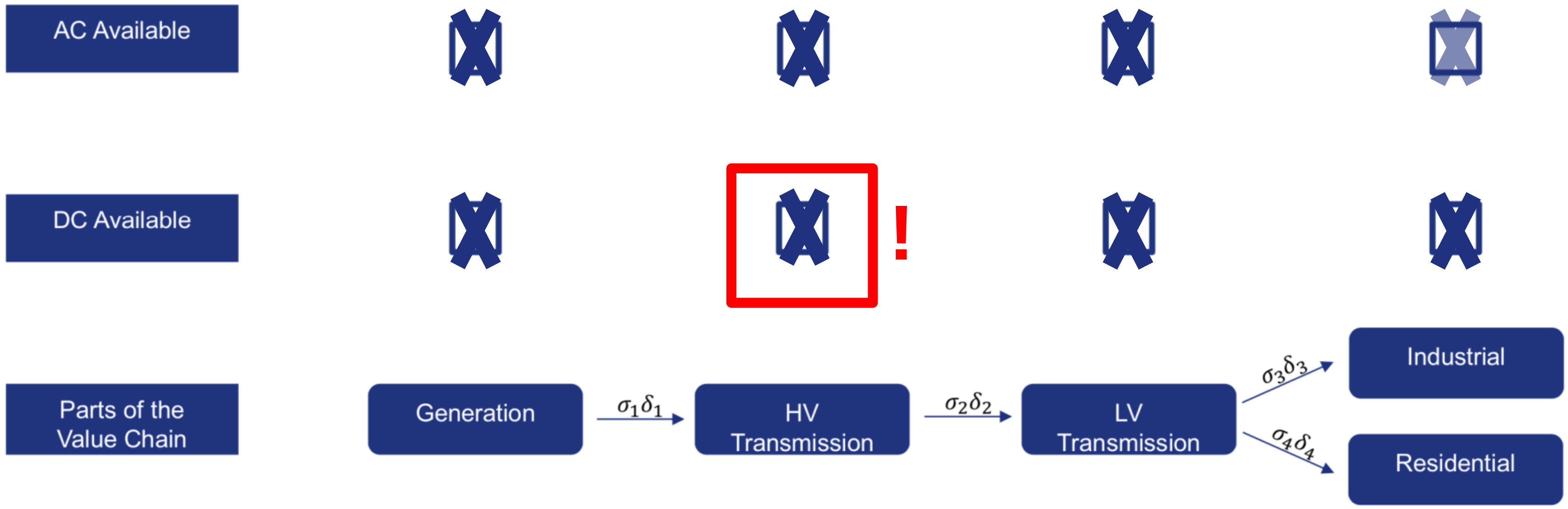
Target Function

$$\min z = \sum_{i=1}^{n} \sigma_x\delta_x$$

σ_x	$\in \{0; 1\}$
δ_x	$\in \mathbb{R}$

Figure 7: The organizational model (Authors design)

Application of the Organizational Model: t_0



AC Available ☒ ☒ ☒ ☒

DC Available ☒ ☒ ! ☒ ☒

Parts of the Value Chain

Generation $\xrightarrow{\sigma_1\delta_1}$ HV Transmission $\xrightarrow{\sigma_2\delta_2}$ LV Transmission

LV Transmission $\xrightarrow{\sigma_3\delta_3}$ Industrial

LV Transmission $\xrightarrow{\sigma_4\delta_4}$ Residential

Legend	
$\xrightarrow{\sigma_x\delta_x}$	Weighted Consideration of the Grade of Incompatibility ($\delta_x =$ Costs of Gateway Technology x, if $\sigma_x = 1$, meaning Technologies are incompatible)

Target Function

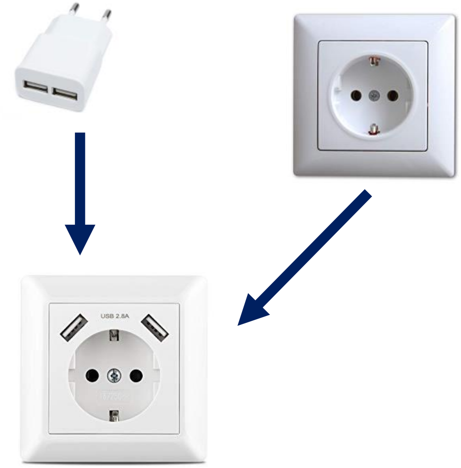
$$\min z = \sum_{i=1}^{n} \sigma_x\delta_x$$

σ_x	$\in \{0; 1\}$
δ_x	$\in \mathbb{R}$

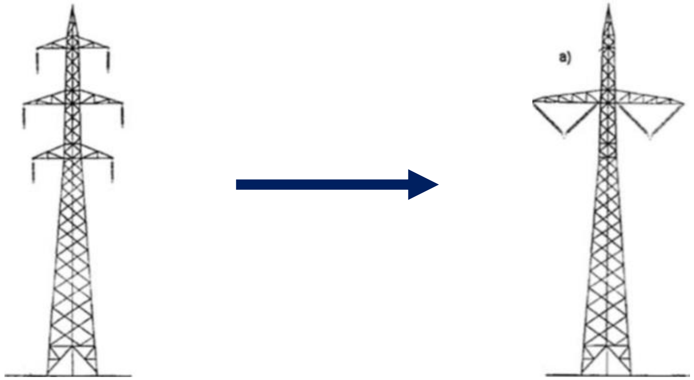
Figure 8: The organizational model (Authors design)

Application of the Organizational Model: t_0

Source: Siemens soicmol201428-09



Source: ME Solshare



Source: Clerici et al. (1991)

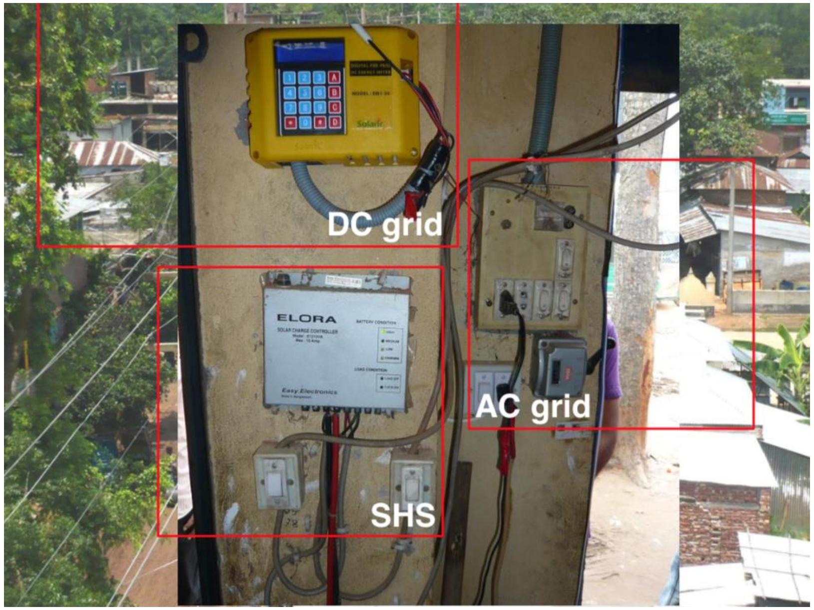
Approach 1: Bottom-Up

Thesis

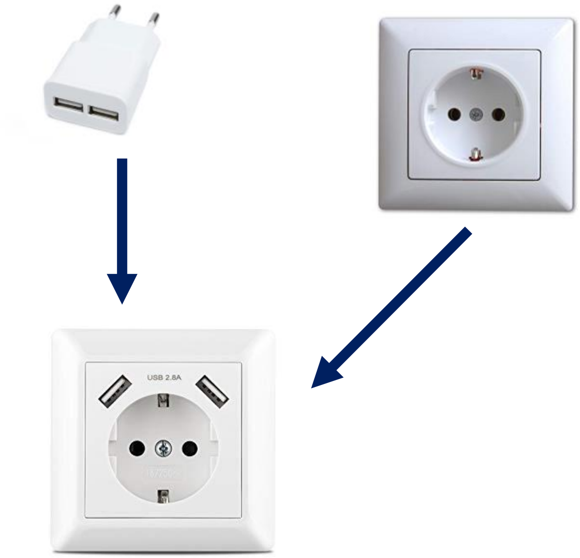
Following movements can be observed: From…

1. in front of the socket to behind the socket closer to the meter,
2. the generation/ before the transmission to the transmission itself.

Supporting that thesis is the clear preference of DC appliances in regions, where no lock-in and/or not already sufficiently existing infrastructure exist.



Source: ME Solshare



Approach 1: Bottom-Up

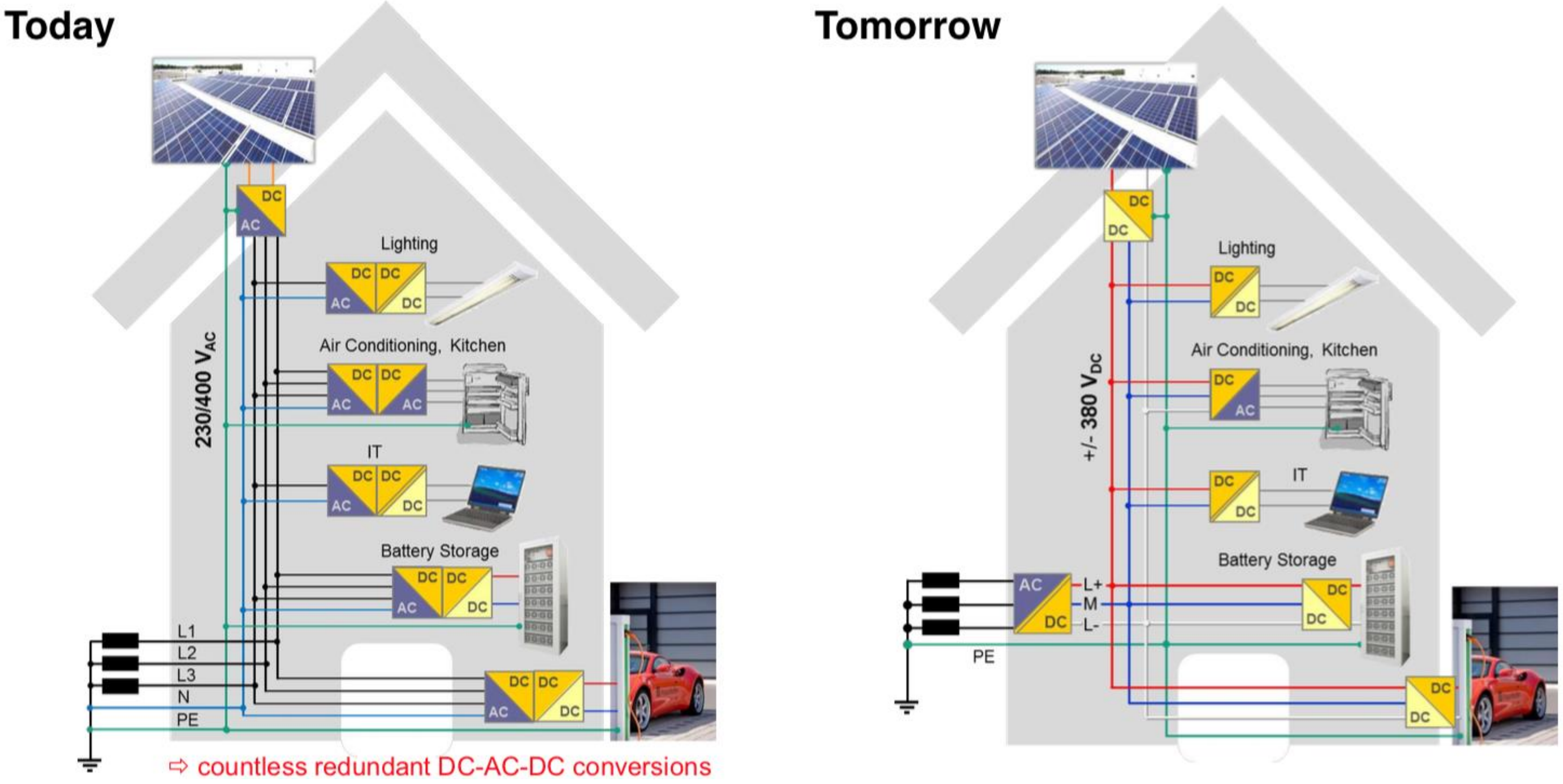


Figure 9: Currents in new built houses (Source: März (2017))

Thesis

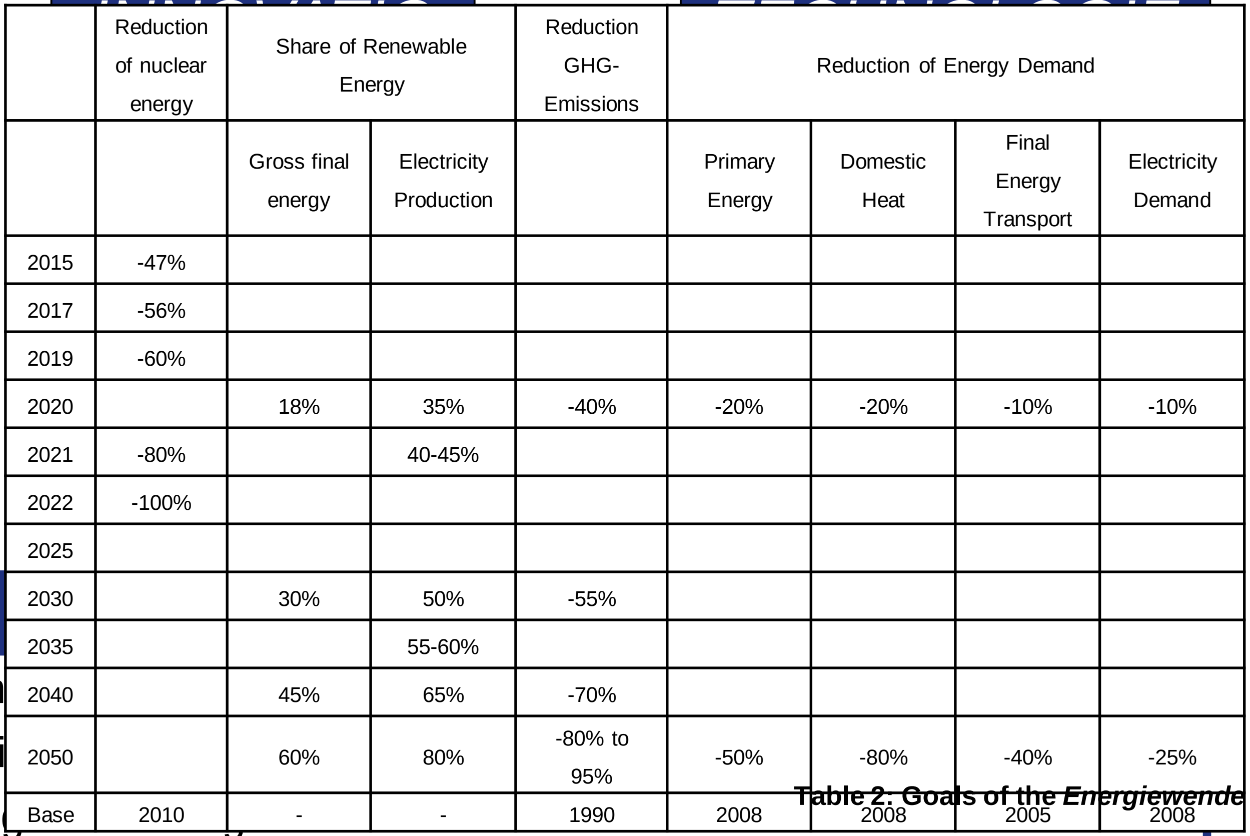
Following movement can be observed: From **in front of the socket to behind the socket closer to the meter**.

Approach 2: Top-Down

Decarbonisation
GOVERNMENT

Digitalisation

Decentralisation



	Reduction of nuclear energy	Share of Renewable Energy		Reduction GHG-Emissions	Reduction of Energy Demand			
		Gross final energy	Electricity Production		Primary Energy	Domestic Heat	Final Energy Transport	Electricity Demand
2015	-47%							
2017	-56%							
2019	-60%							
2020		18%	35%	-40%	-20%	-20%	-10%	-10%
2021	-80%		40-45%					
2022	-100%							
2025								
2030		30%	50%	-55%				
2035			55-60%					
2040		45%	65%	-70%				
2050		60%	80%	-80% to 95%	-50%	-80%	-40%	-25%
Base	2010	-	-	1990	2008	2008	2005	2008

Table 2: Goals of the *Energiewende*

The 3-D driven DC

Crucial Developments of the s. c. th

1. Decarbonisation, consisting mai
2. Digitalisation, empowered throu
3. Decentralisation, as a necessity for the decentral energy generation using especially Solar- and Wind energy.

Approach 2: Top-Down

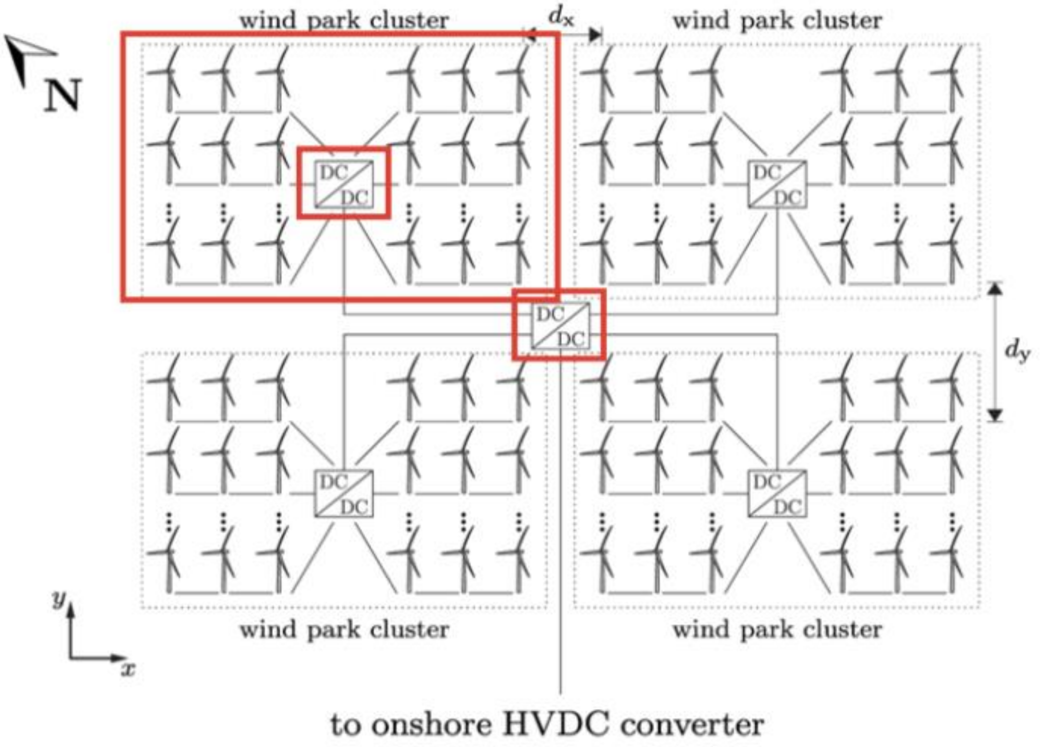


Figure 10: Hybrid application of the currents (Source: Stieneker 2017)

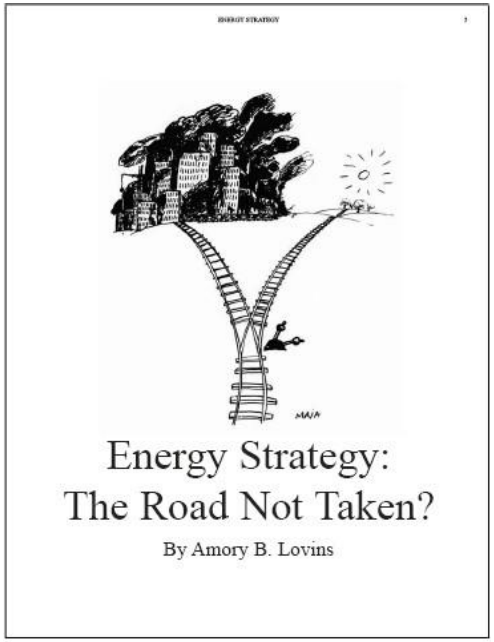
Progressing of direct current within a alternating current dominated system

AC	*DC*
Less conversion losses	Less conduction losses

Agenda

1) Introduction and Motivation
2) Basic Theory and Organizational Model
3) Application of the Organizational Model
4) Conclusion

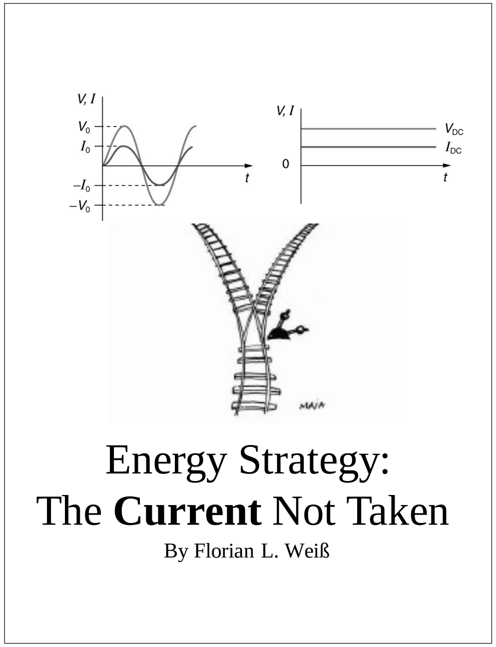
Conclusion



ENERGY STRATEGY

Energy Strategy:
The Road Not Taken?

By Amory B. Lovins



Energy Strategy:
The **Current** Not Taken

By Florian L. Weiß

“The Road Not Taken” inspires “The Current Not Taken”

1. The environment is attractive → due to necessity of infrastructural redesign and adjustments
2. Technological innovations now enable and increase potential of DC based technology

Since we are again at a point of time, when **we can decide** between either AC or DC, we find ourselves in a future system characteristic’s determining position.

References (Excerpt)

Beckers, Thorsten, Florian Gizzi, and Klaus Jäkel. 2012. “An Analytical Approach for System Goods.” Berlin: TU Berlin.

David, Paul A. 1985. “Clio and the Economics of QWERTY.” *The American Economic Review* 75 (2): 332–37.

De Doncker, Prof. Dr. ir. Dr. h.c. Rik W. 2017. ‘The War of Currents – How DC Technology Lost the Battle 150 Years Ago, but May Win the War Exploiting Its Full Potential in a Volatile, Liberalized Energy World’. RWTH Aachen University.

Groh, Sebastian, Daniel Philipp, Brian Edlefsen Lasch, Hannes Kirchhoff, Didar Islam, M. Rezwan Khan, and Shahriar Chowdhury. 2014. “The Battle of Edison and Westinghouse Revisited: Contrasting AC and DC Microgrids for Rural Electrification.” Berlin Institute of Technology.

Hughes, Thomas Parke. 1993. *Networks of Power: Electrification in Western Society, 1880-1930*. Baltimore, USA; London, UK: Johns Hopkins University Press.

Katz, Michael L., and Carl Shapiro. 1994. “System Competition and Network Effects.” *Journal of Economic Perspectives* 8, Nr.2.

North, Douglass C. 1990. *Institutions, Institutional Change and Economic Performance*. Cambridge: Cambridge University Press.

Shy, Oz. 1995. *Industrial Organization: Theory and Applications*. Cambridge, Mass: The MIT Press.

Vossos, Vagelis, Stephen Pantano, Ruby Heard, and Rich Brown. 2017. “DC Appliances and DC Power Distribution.” Berkeley, CA, USA: Lawrence Berkeley National Laboratory.

Weiss, Florian, Richard Groß, Sarah Linowski, Christian von Hirschhausen, Ben Wealer, and Timon Zimmermann. 2019. “How Incumbents Are Adjusting to the Changing Business Environment: A German Case Study.” Chapter 17. Consumer, Prosumer, Prosumager 1st Edition. Waltham, WA: Elsevier.

Thank you for your Attention!

Contact

Florian Weiß
flw@wip.tu-berlin.de