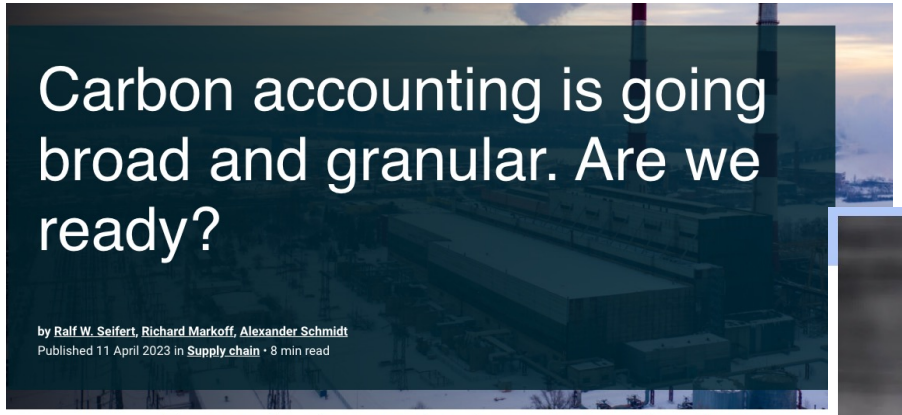
Carbon-Aware Global Routing In Path-Aware Networks

Jonghoon Kwon
ETH Zürich

Why CO_2-Awareness?



Europe is about to implement a major change in the reporting standards and requirements for carbon as part of the European Green Deal. These changes will require more companies to account for their carbon footprints over a broader scope and in greater granular detail. The authors explore the implications of this major policy shift.

The economic effects of carbon pricing

Diego Känzig, Maximilian Konradt / 12 Aug 2023

Carbon pricing policies are critical tools to mitigate the effects of climate change. This column examines the impact of European carbon pricing policies on the economy, contrasting the common carbon market with national carbon taxes. The authors find that

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EU commission chief asks G20 to join global carbon pricing

Reuters

September 9, 2023 11:43 AM GMT+2 · Updated 5 days ago

ident Ursula von der Leyen gestures during a joint press statement with Philippine President Malacanang Presidential Palace in Manila, Philippines, July 31, 2023. Aaron Favila/POOL via e Licensing Rights

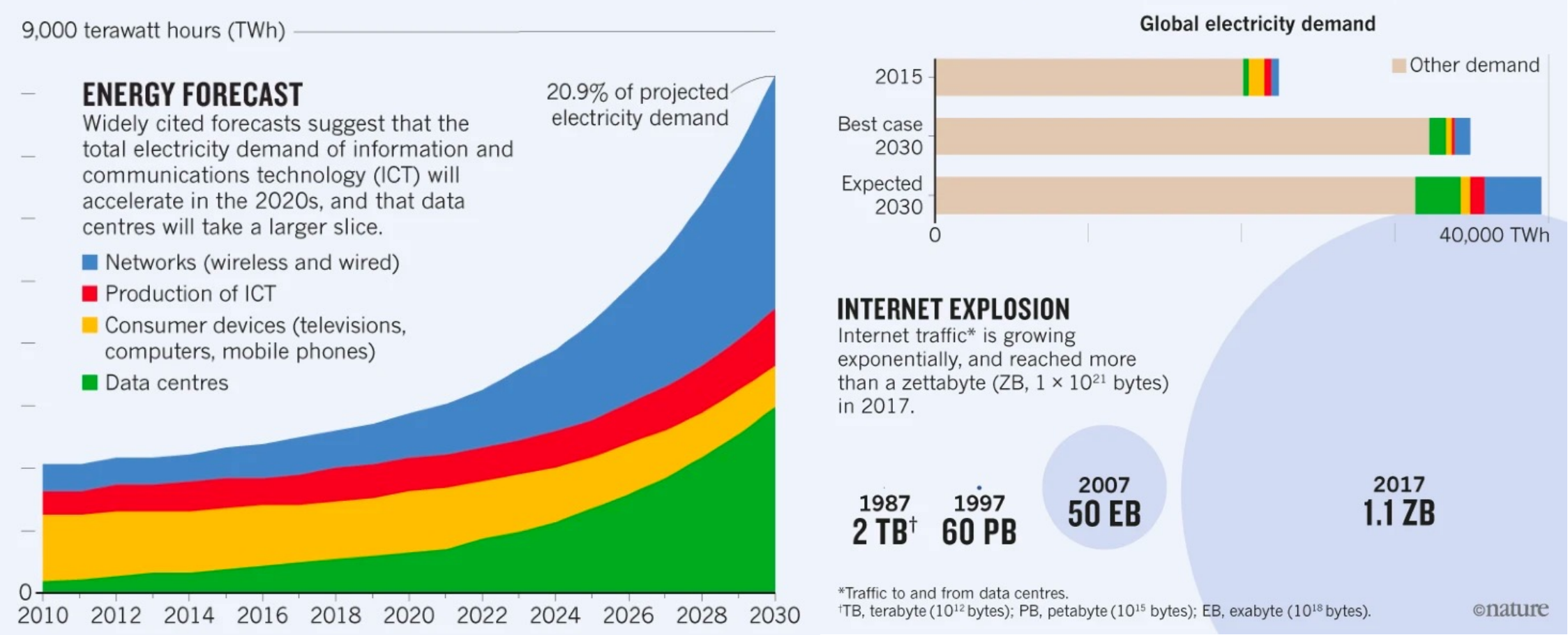
Reuters) - The European Commission president asked G20 leaders on posal to set up global carbon pricing.

ing a price on carbon to help meet their climate goals in the form of a tax trading (ETS), or cap-and-trade, system.

An email with attachment is account for 50g of CO_2

<source: ictfootprint.eu>

ICT Carbon Footprint



<Source: nature.com>

Is It Possible in Today's Internet?

ISPs select inter-domain paths

Endpoints have no control over paths

No means of carbon transparency

Carbon-Aware Networking?

- Path transparency

Carbon-Aware Networking?

- Path transparency
- Carbon intensity estimation

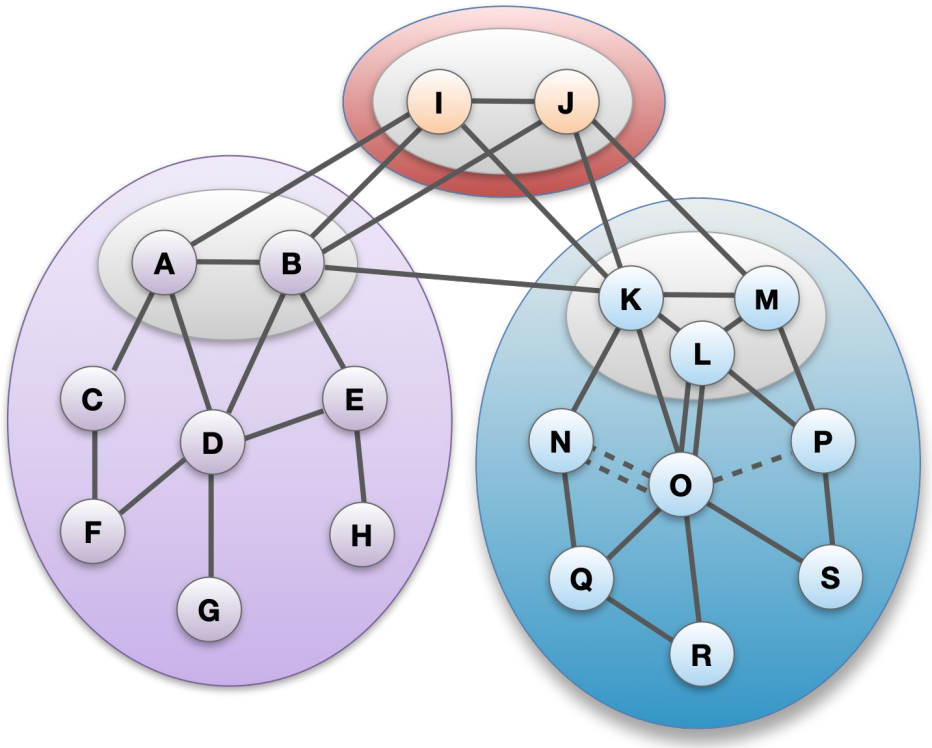
Carbon-Aware Networking?

- Path transparency
- Carbon intensity estimation
- Endpoint path control

Already Possible with The Future Internet Architecture

SCION

- Path-based Network Architecture

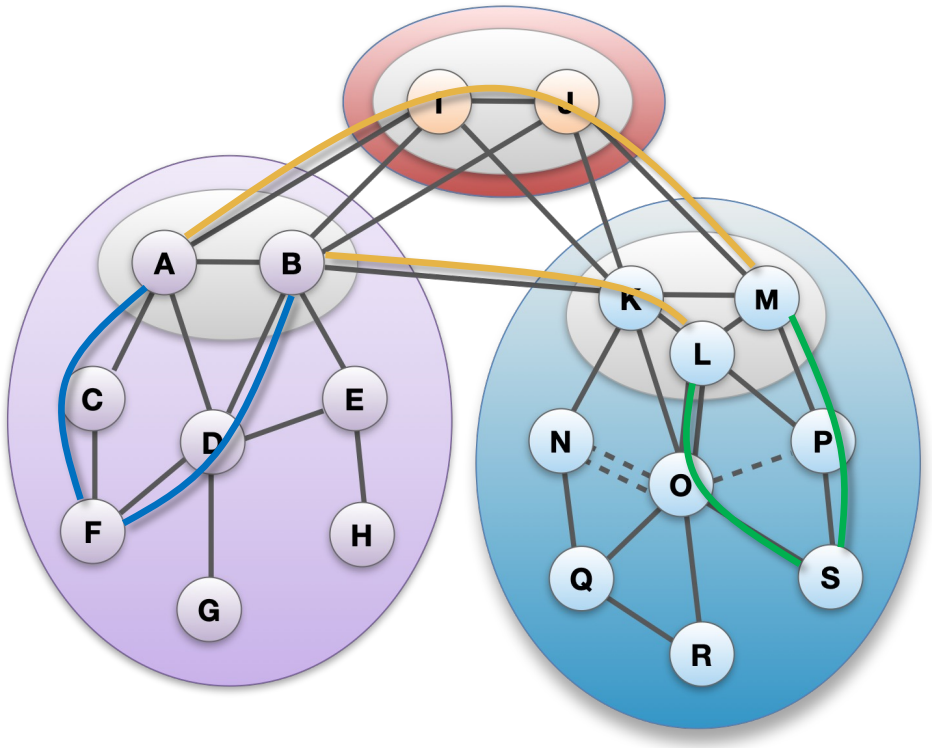


Already Possible with The Future Internet Architecture

- Path-based Network Architecture

Control Plane - Routing

- Constructs and Disseminates Path Segments



Already Possible with The Future Internet Architecture

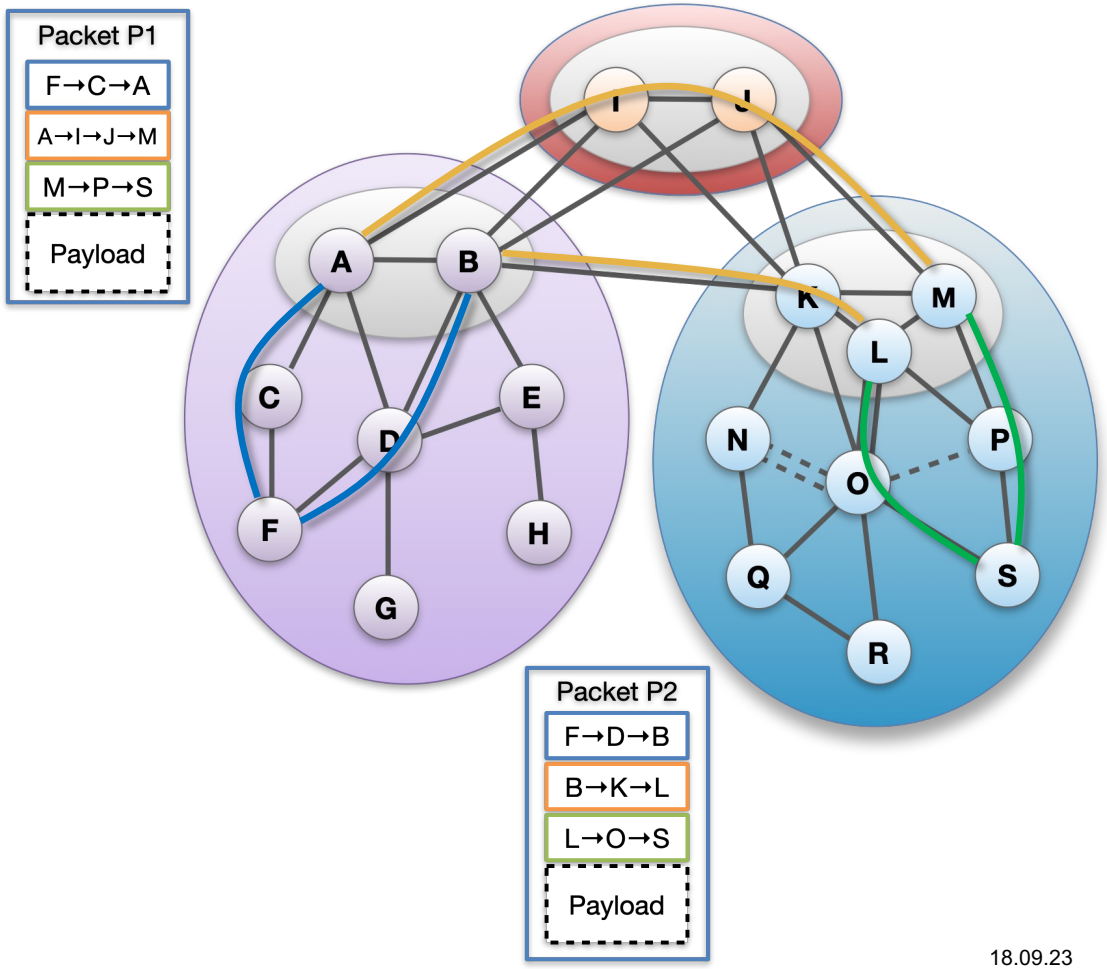
- Path-based Network Architecture

Control Plane - Routing

- Constructs and Disseminates Path Segments

Data Plane - Packet forwarding

- Combine Path Segments to Path
- Packets contain Path
- Routers forward packets based on Path
  - Simple routers, stateless operation

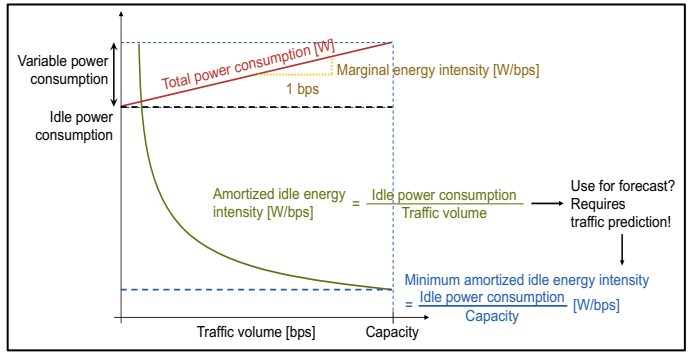


Carbon-Aware Inter-Domain Routing

- CIRo: Carbon-Aware Inter-Domain Routing based on Path-Aware Networking

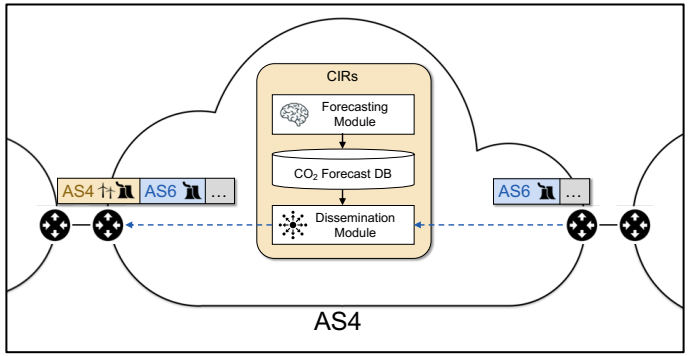
Carbon-Intensity Forecasting

Model for carbon intensity of Internet paths



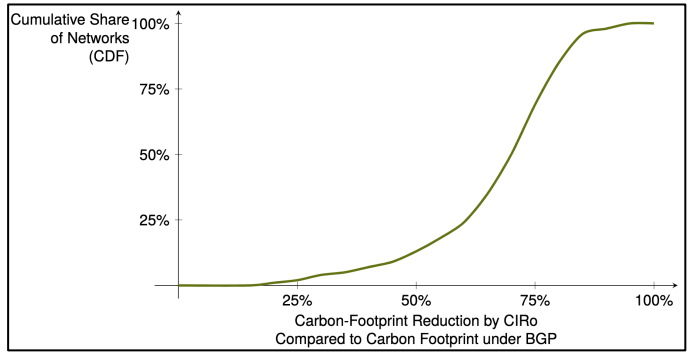
Carbon-Information Dissemination

System for timely communication of forecasts



Carbon-Footprint Impact Analysis

Simulation on data-backed large-scale topology



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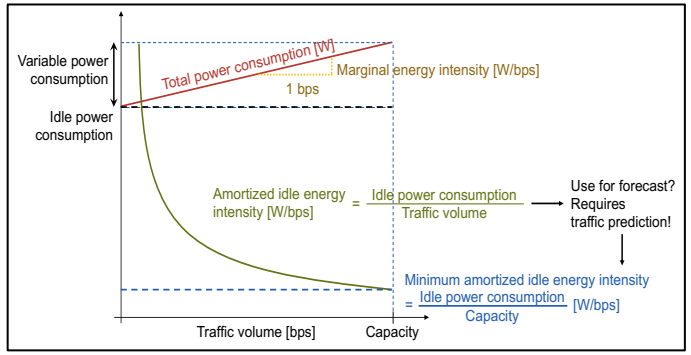

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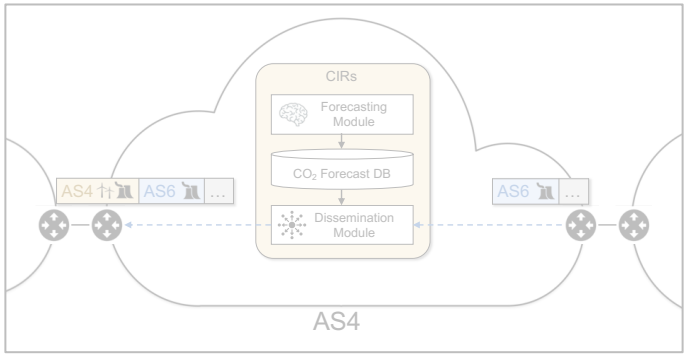

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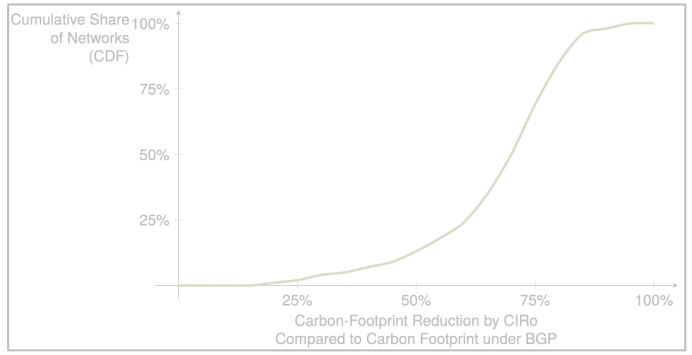

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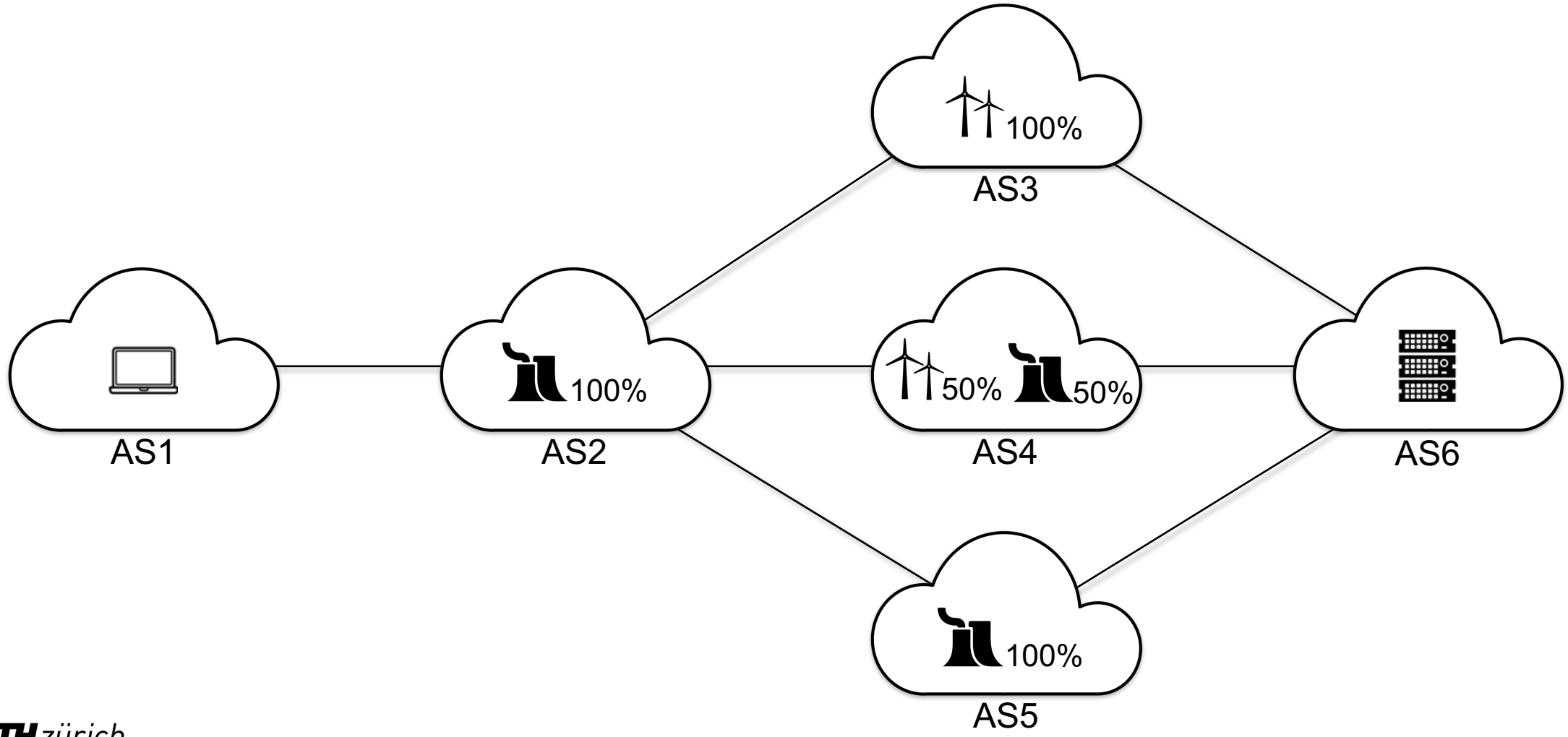

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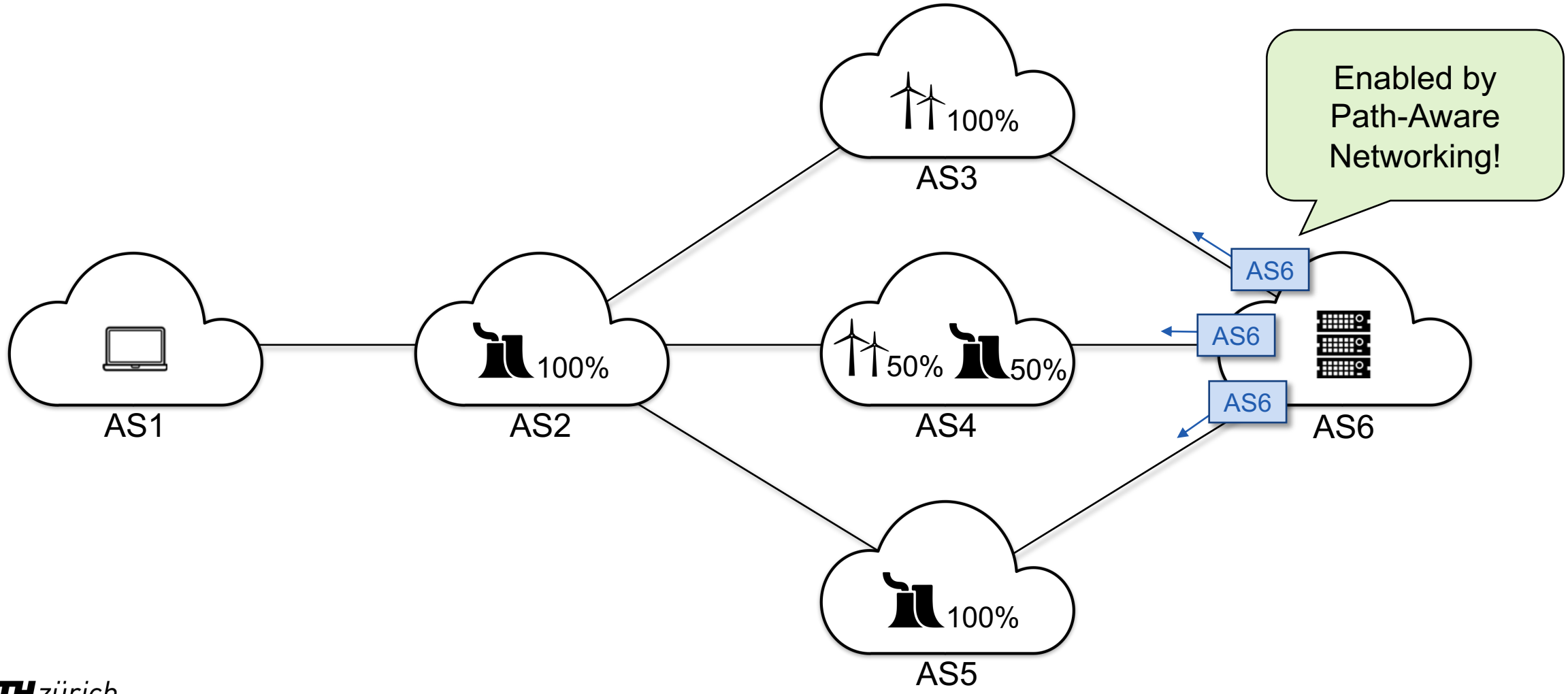

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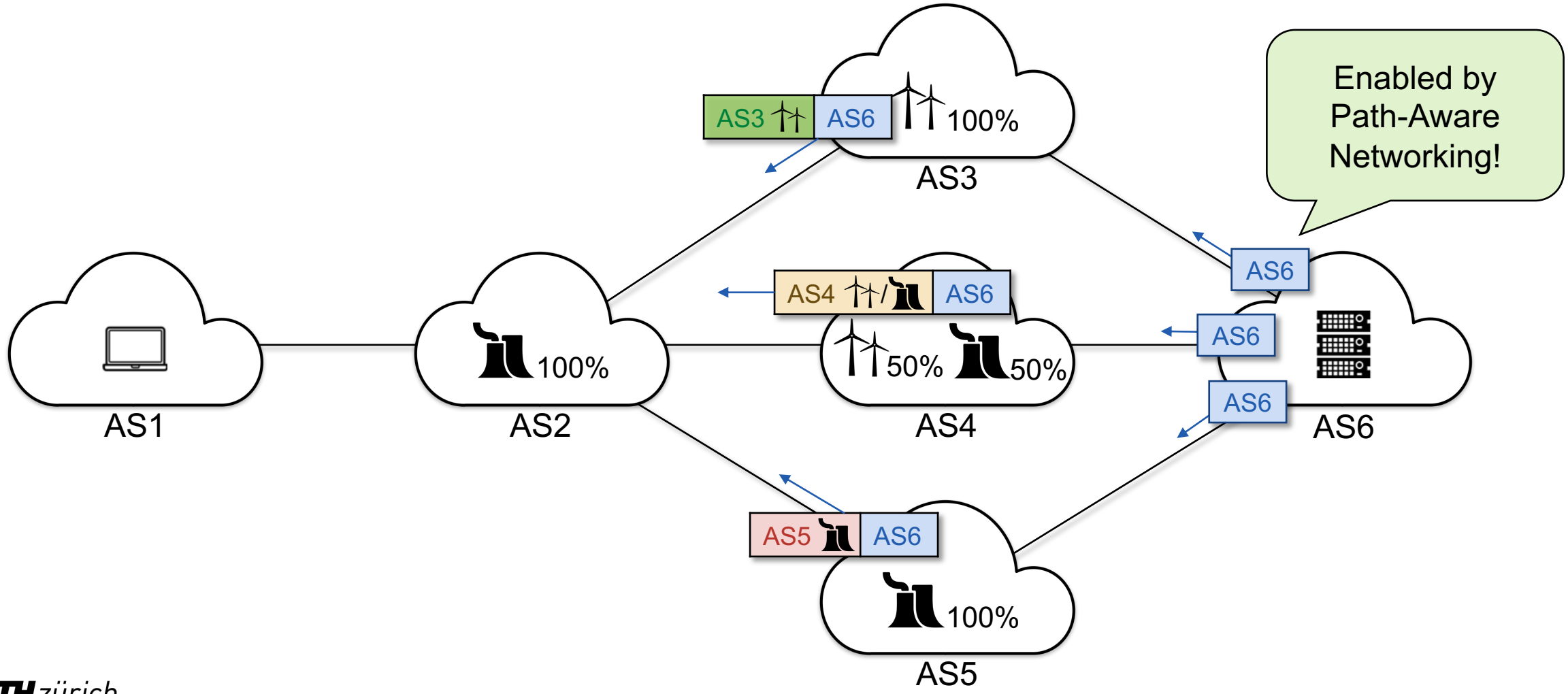

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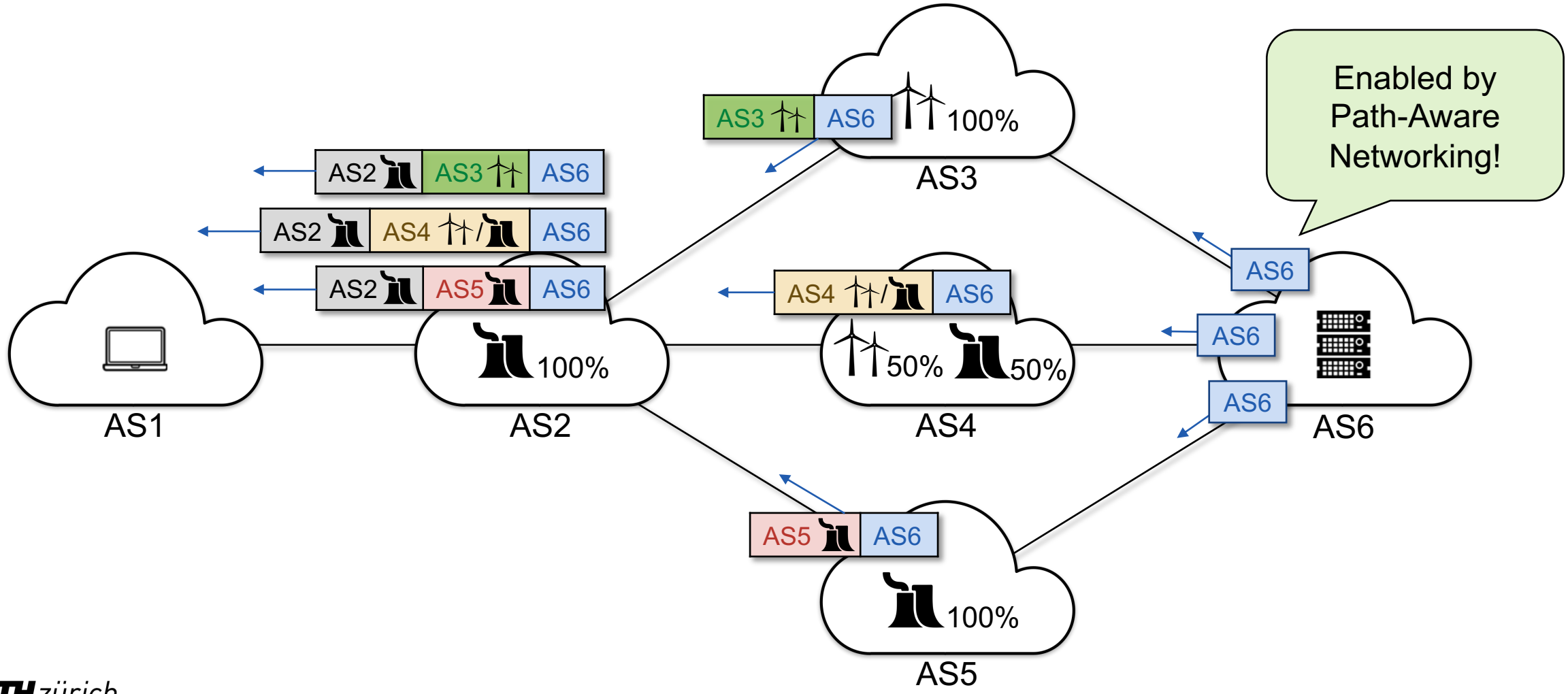

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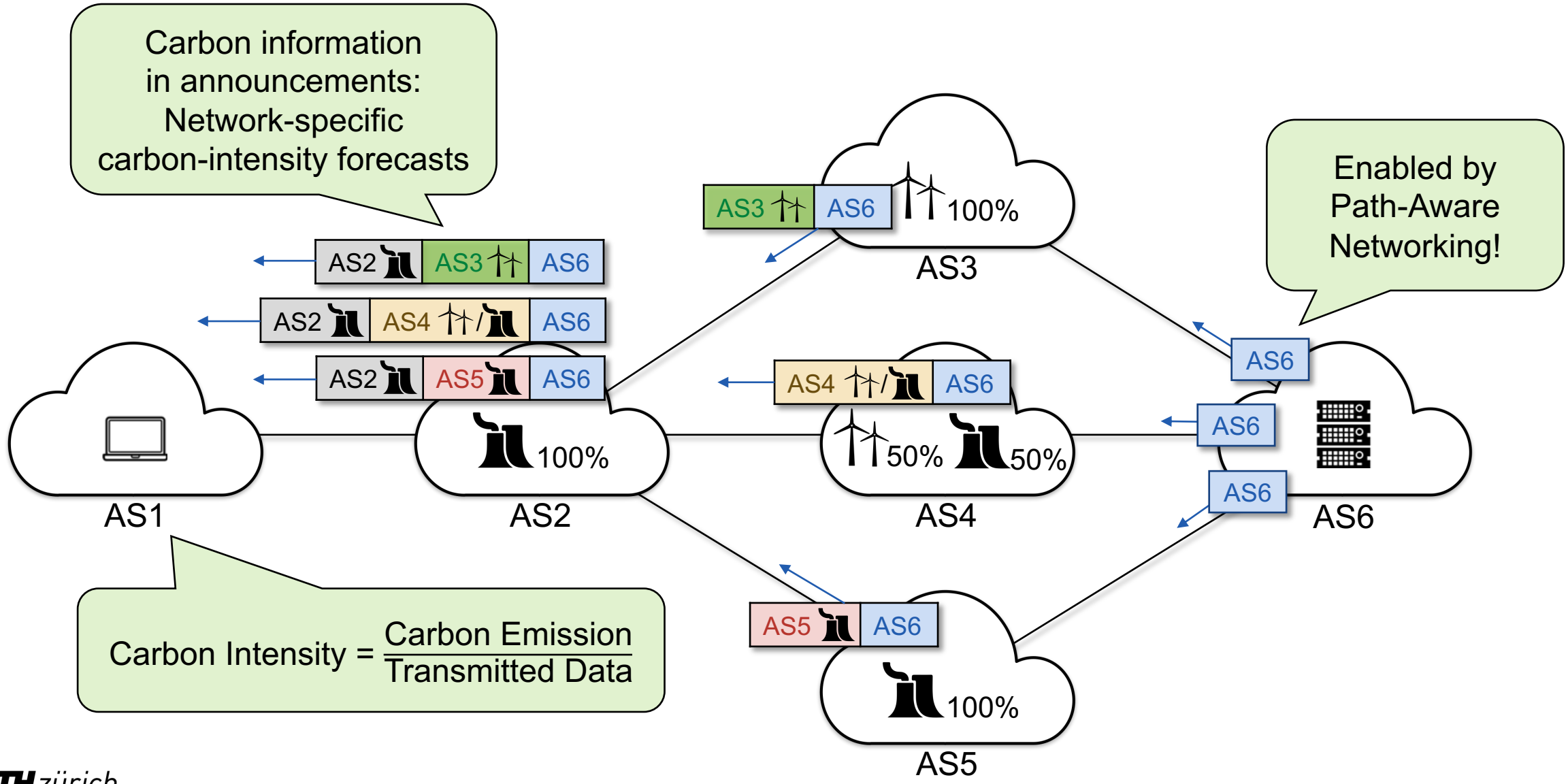
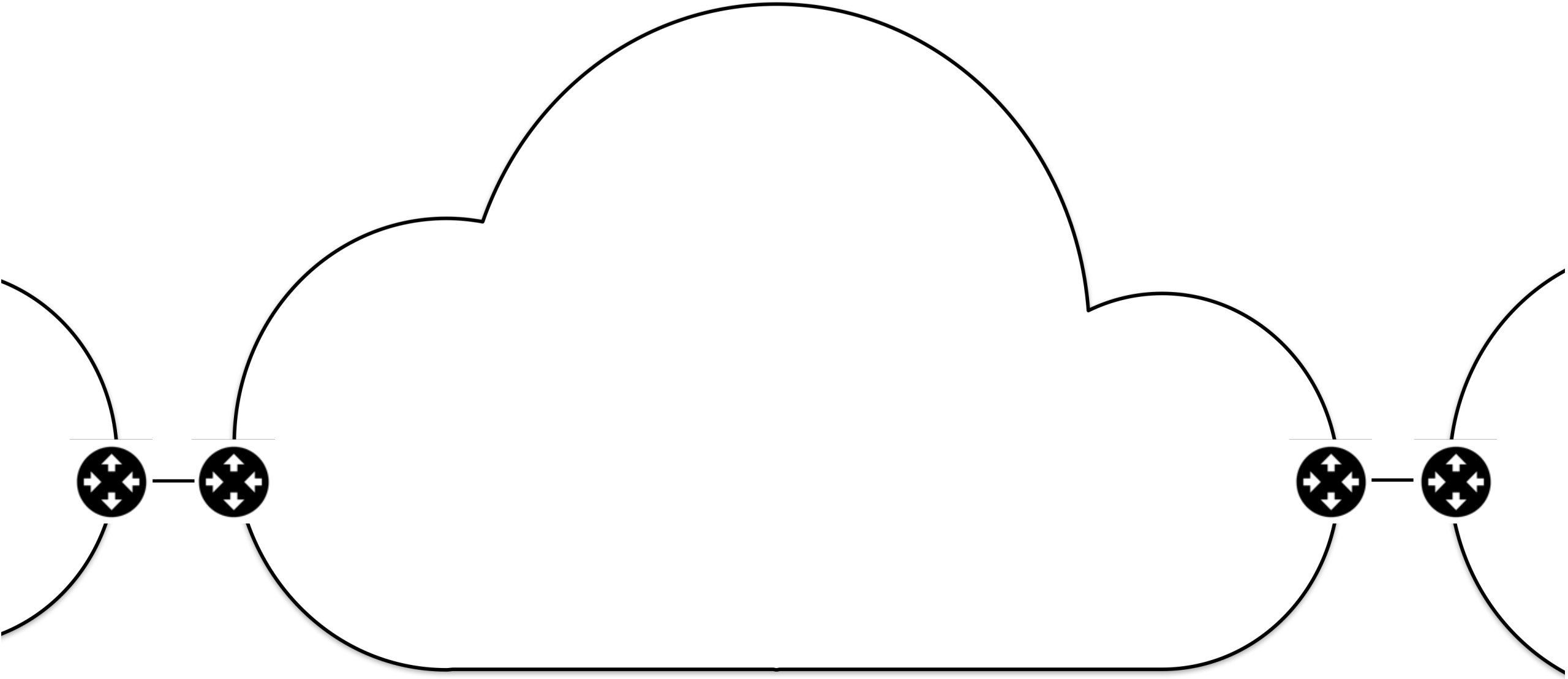


Network-Specific Carbon Intensity



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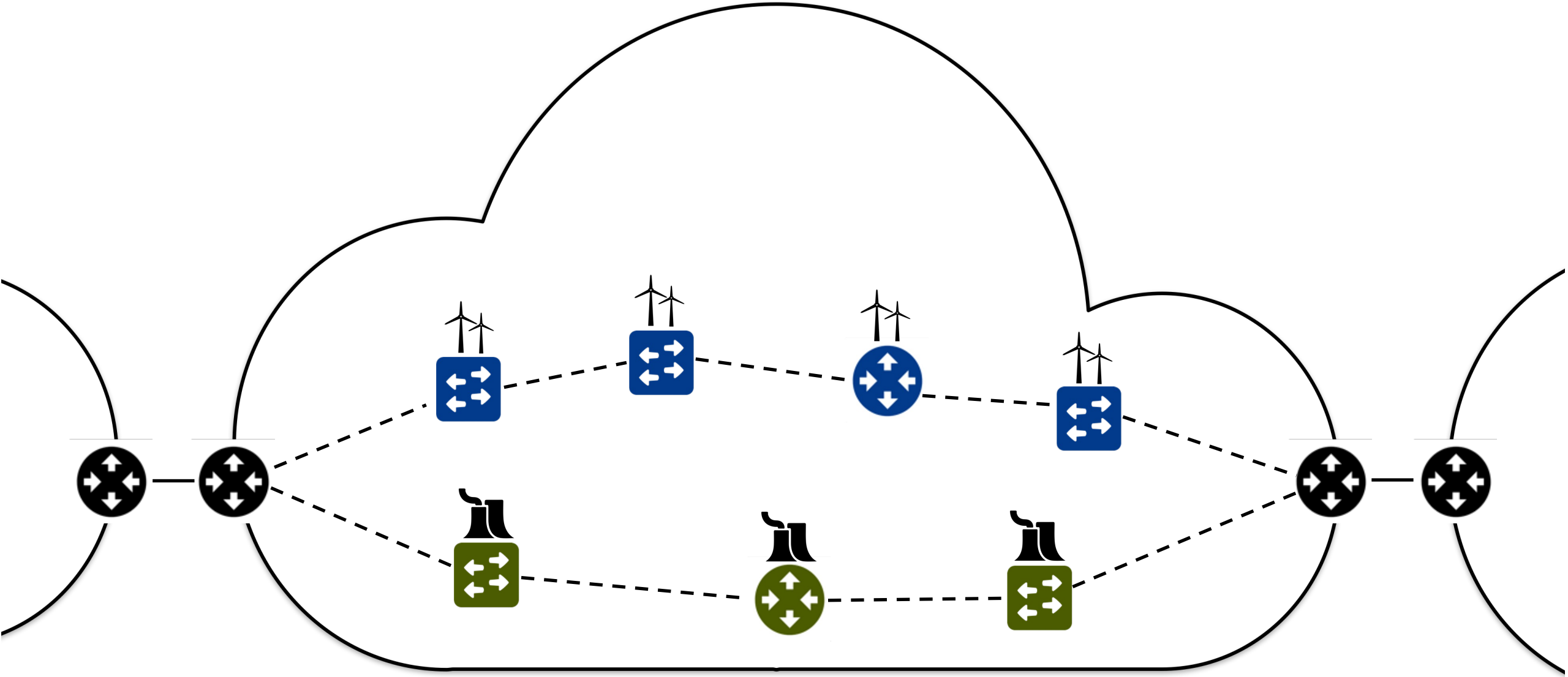
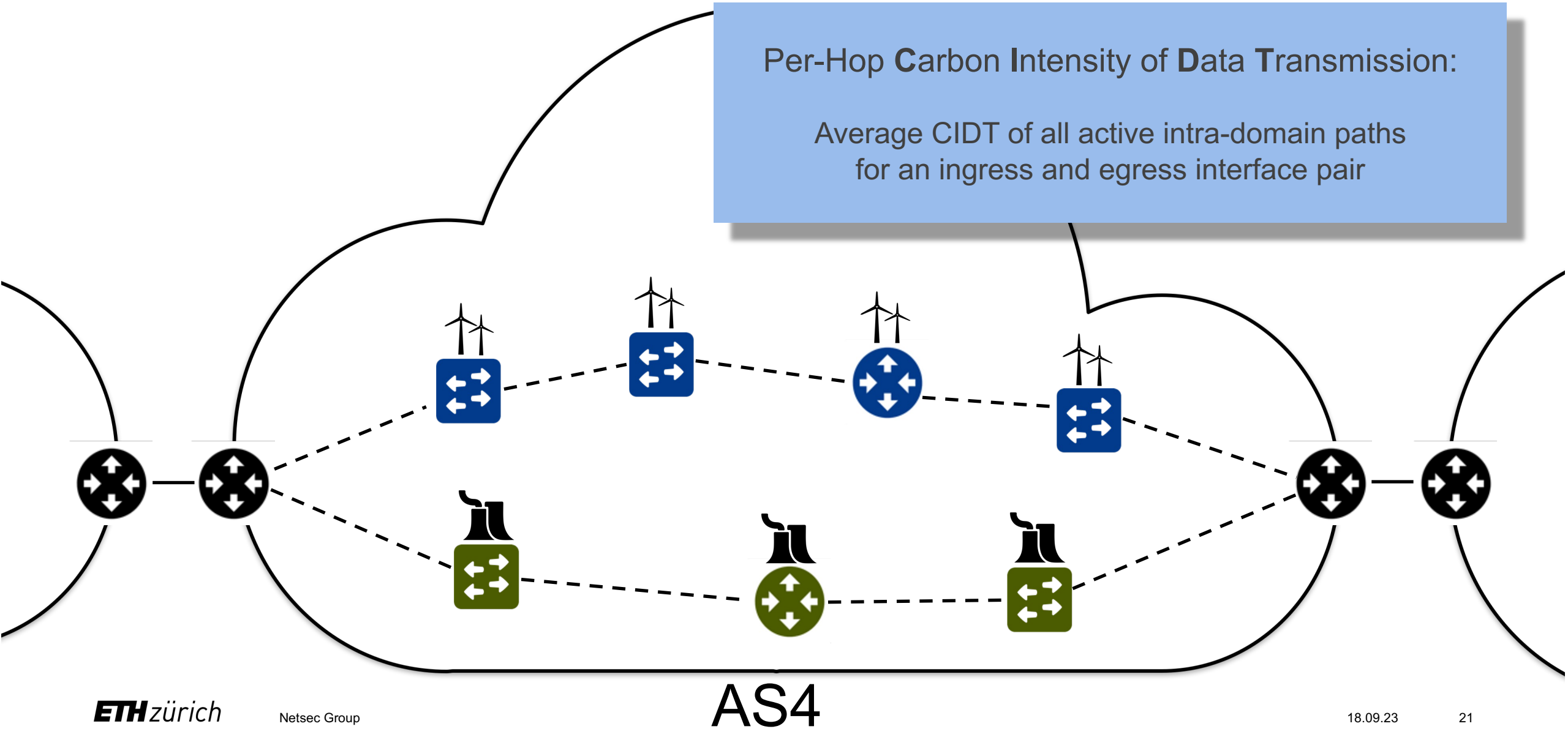


Network-Specific Carbon Intensity

Per-Hop **C**arbon **I**ntensity of **D**ata **T**ransmission:

Average CIDT of all active intra-domain paths
for an ingress and egress interface pair



Device-Specific Carbon Intensity

- Carbon Intensity of Data Transmission = $\frac{\text{Carbon Emission}}{\text{Transmitted Data}}$

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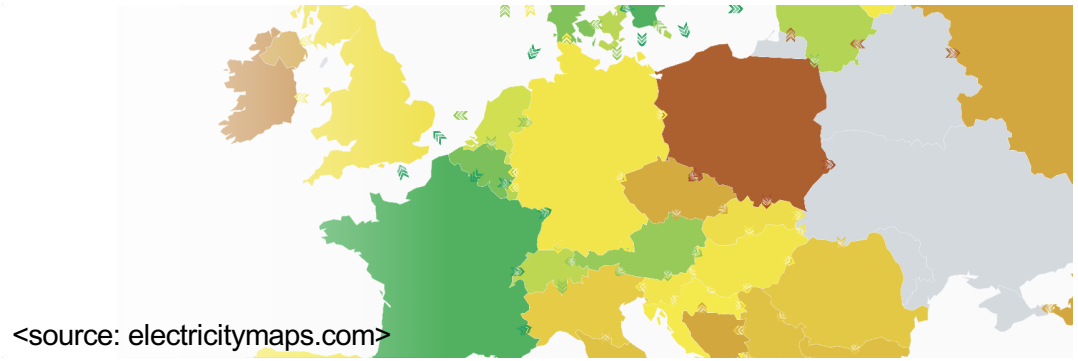
① Carbon-Intensity of Electricity

Device Location ⊕ Electricity-Grid Forecast



<source: electricitymaps.com>

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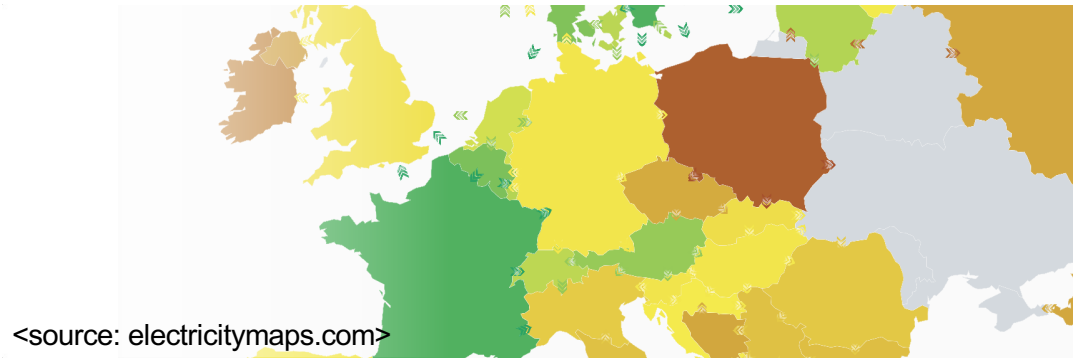

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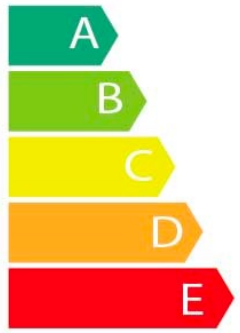
② Energy-Intensity of Data Transmission

Device Power Profile

Mode	Current	Power Consumption [mW]	
	[mA]	@ 1.8 V	@ 3.6 V
Power Down	700 nA	< 1.26 uW	< 2.52 uW
CPU Active	4.1	7.38	14.76
Receiving	6	10.8	21.6
Transmitting	14.5	26.1	52.2
CPU Active + TX	18.6	33.48	66.96



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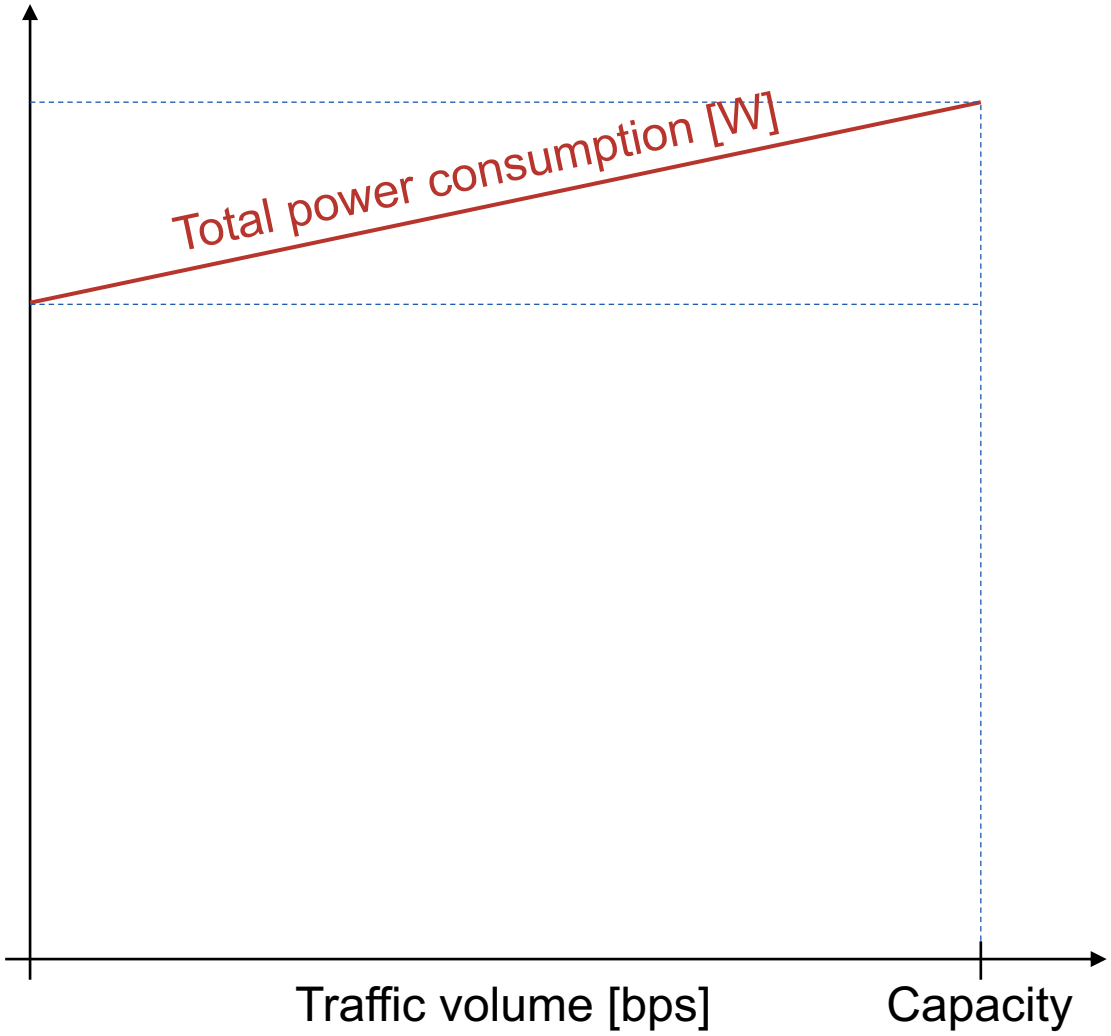

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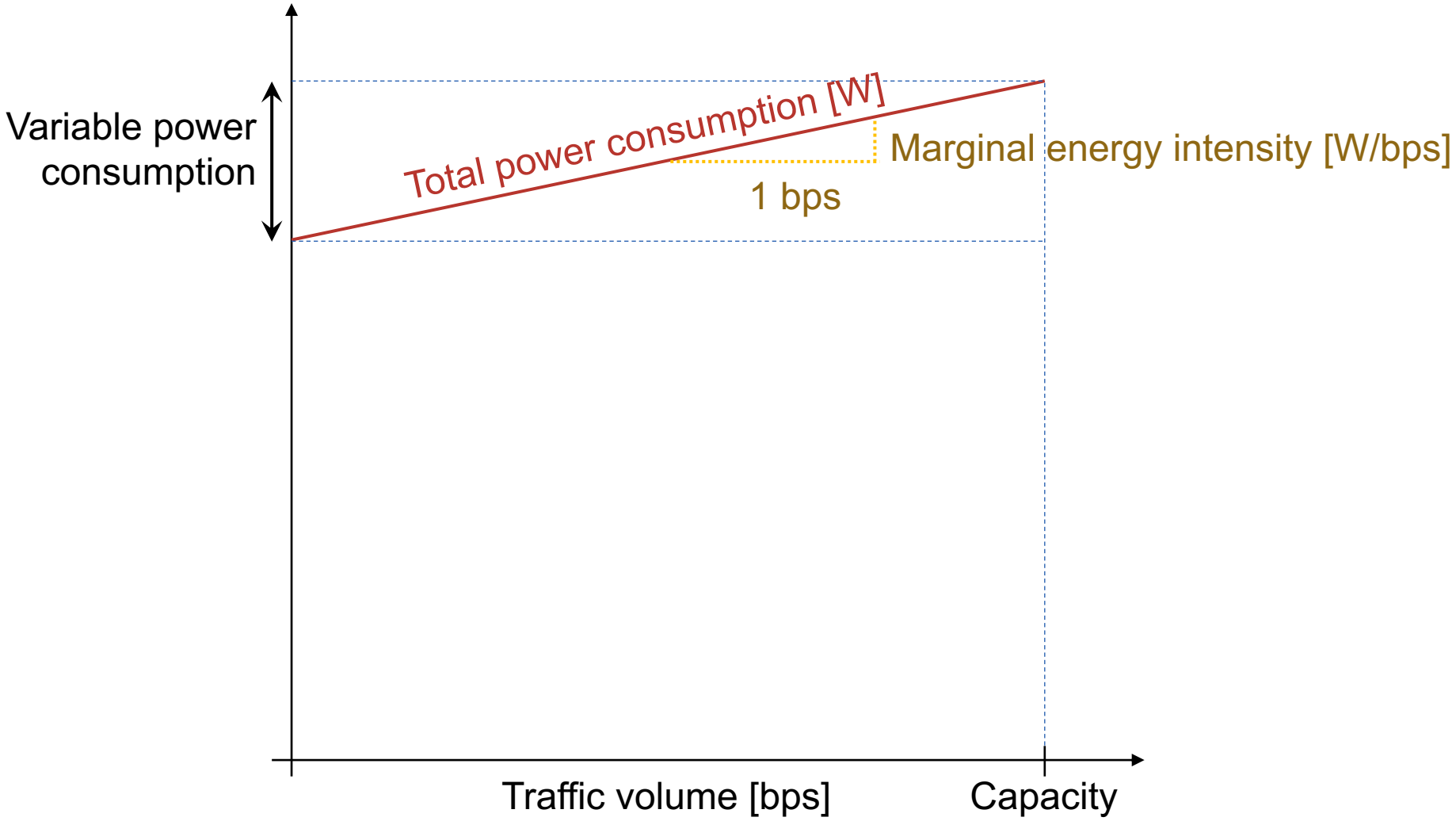

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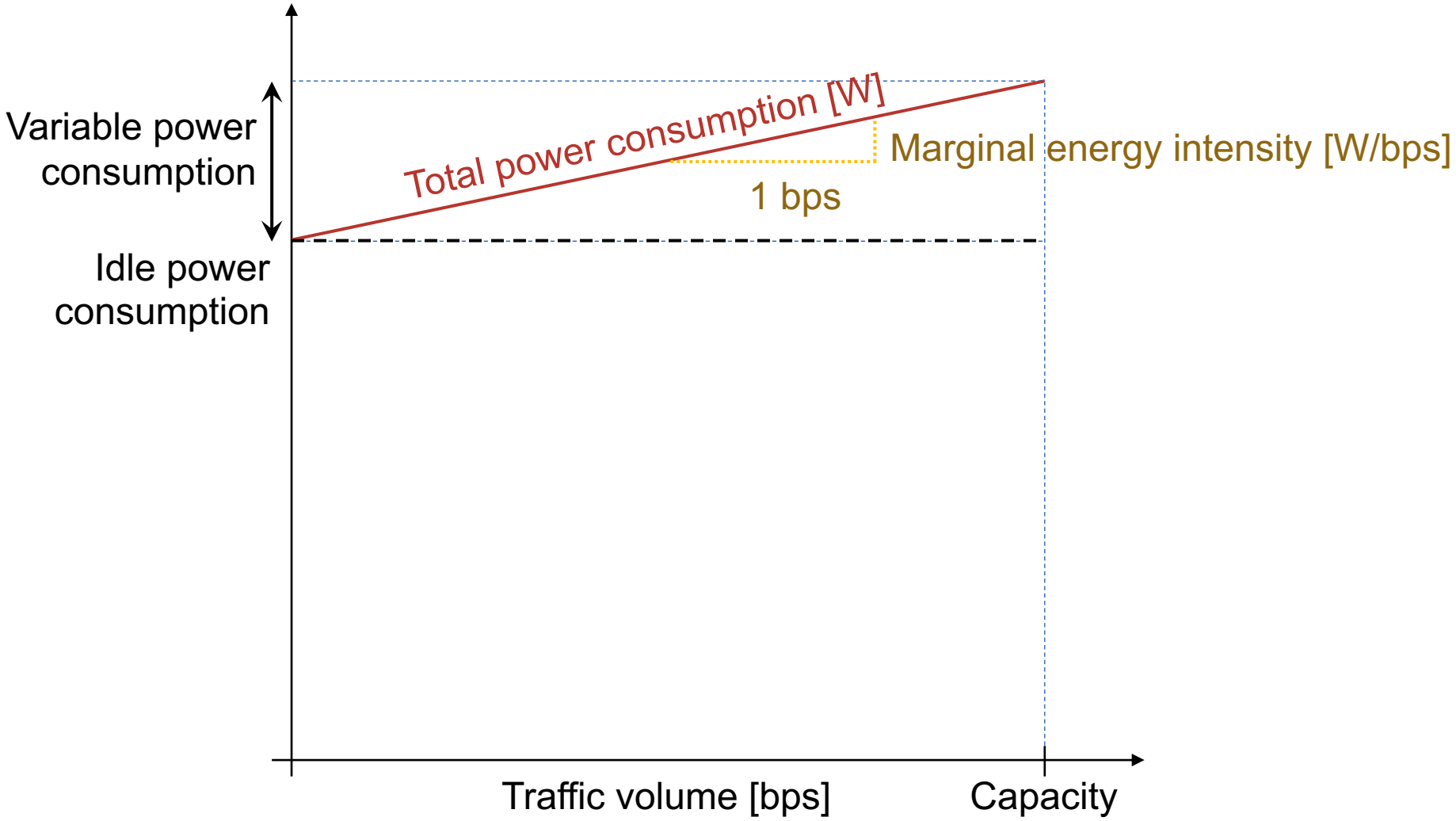

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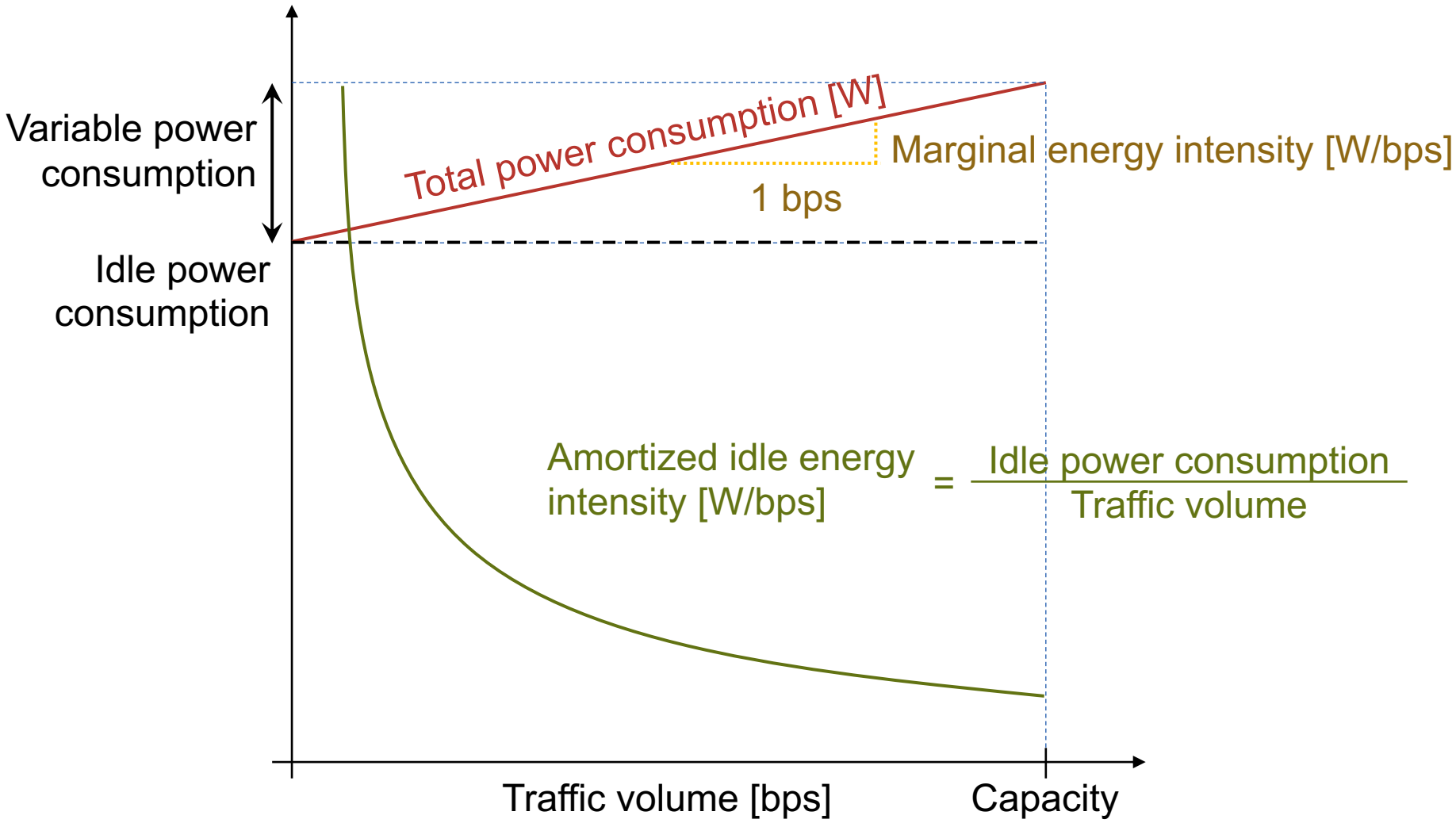

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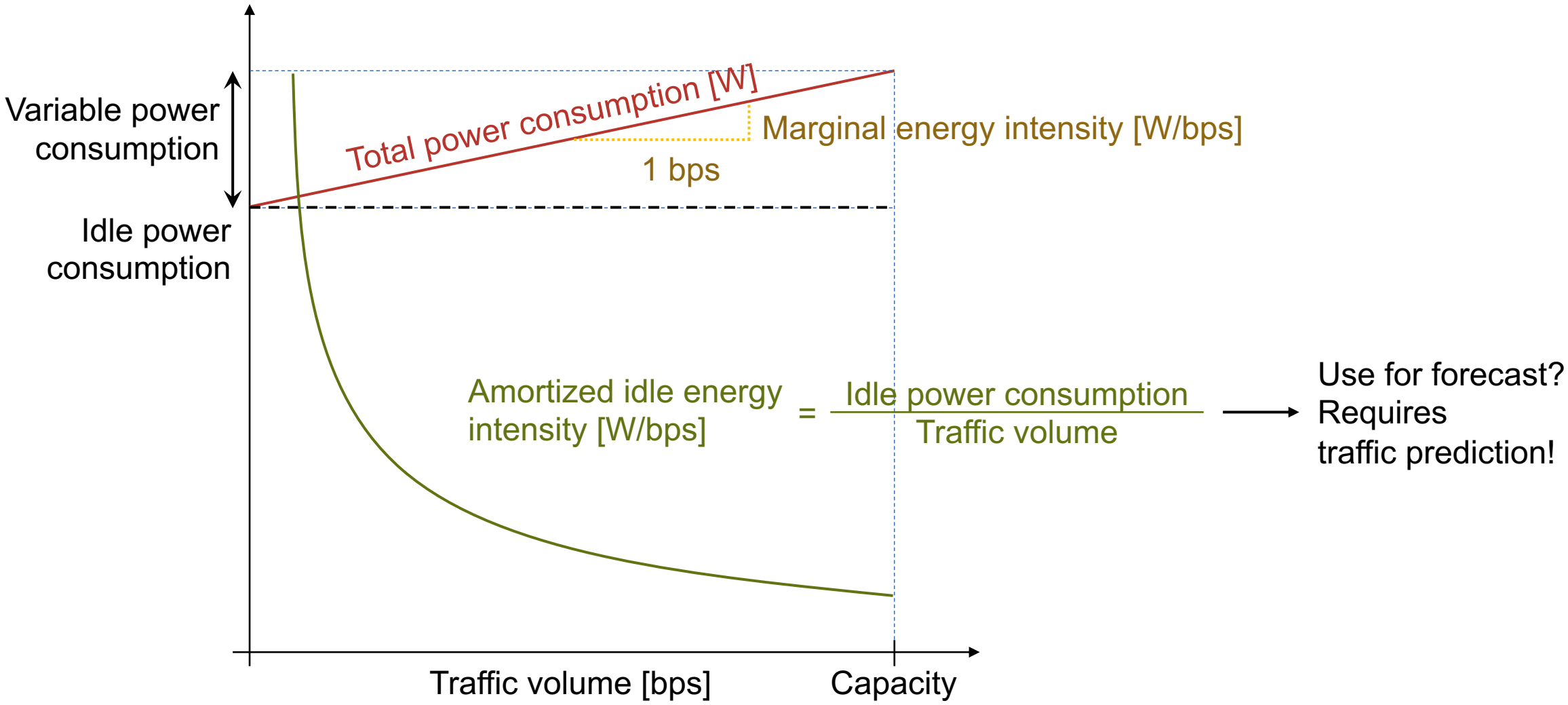

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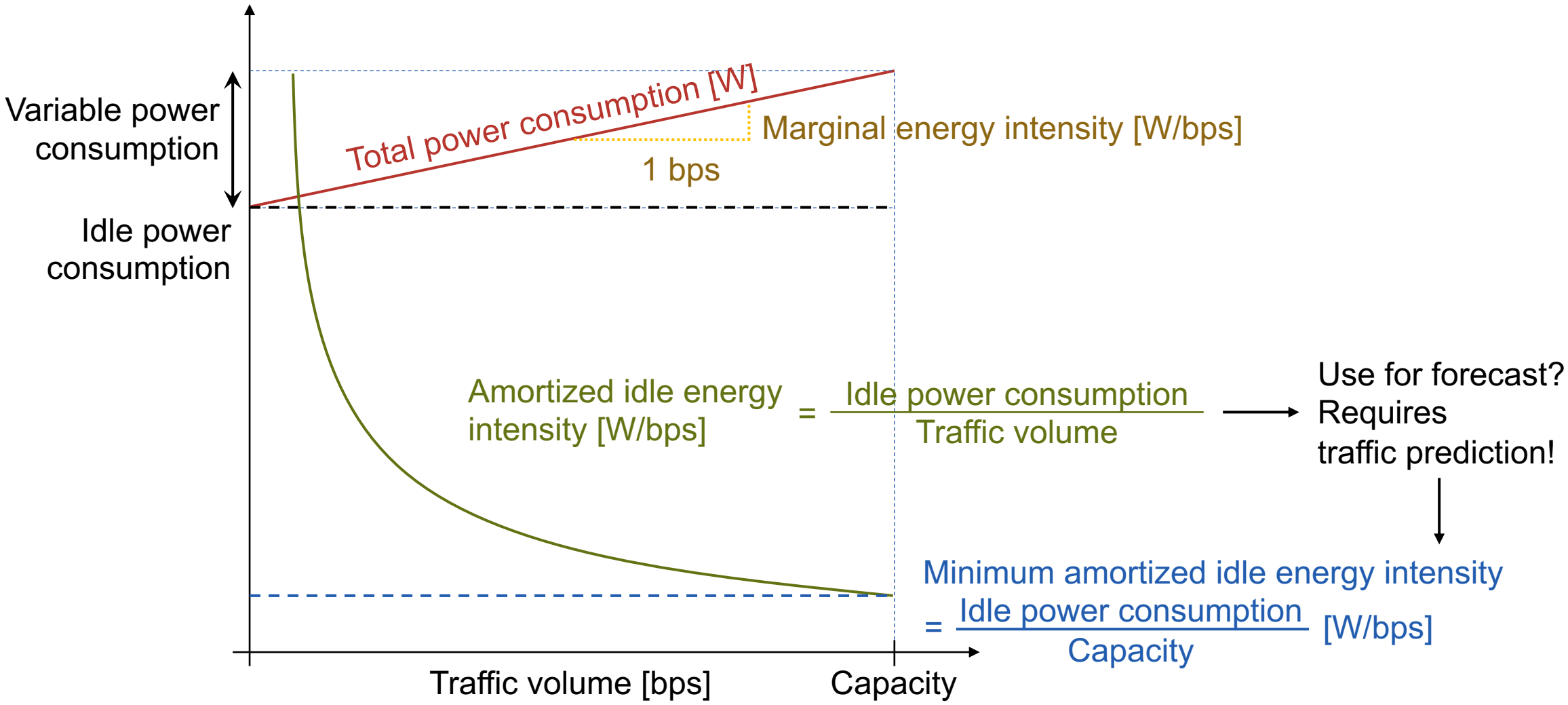

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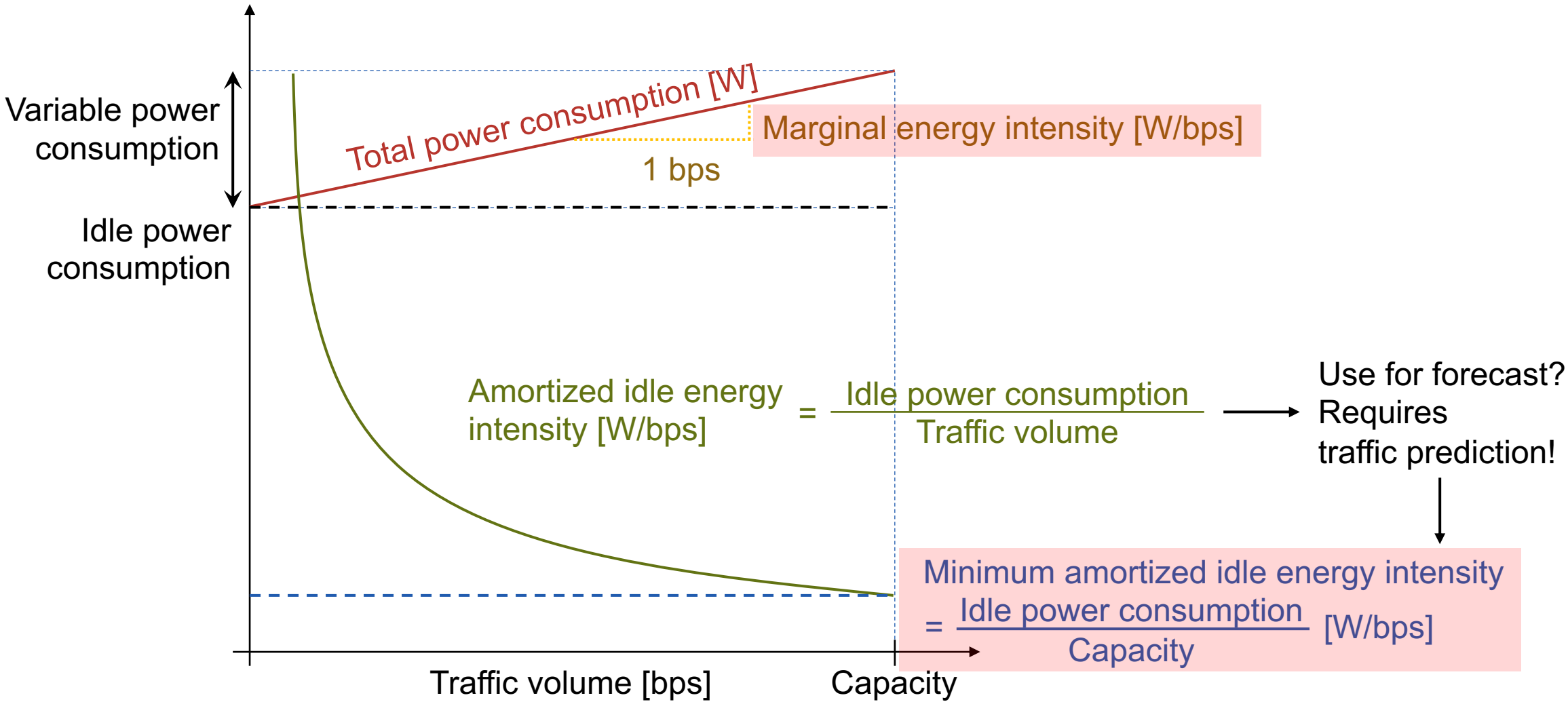
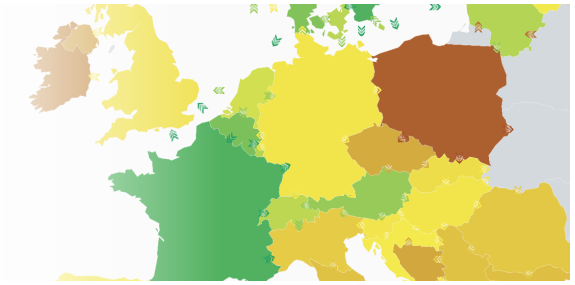
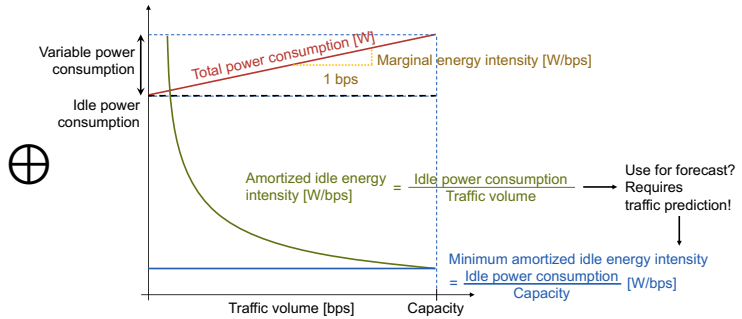


Carbon Intensity Forecasting: Summary

Carbon intensity of devices





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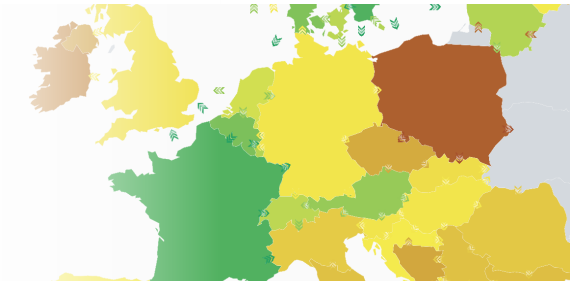
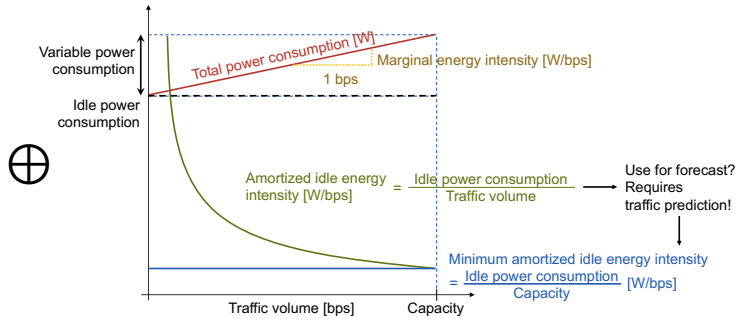
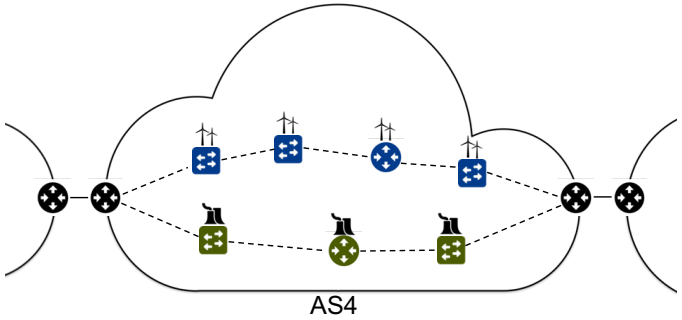




Carbon intensity of intra-network paths



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Carbon intensity of intra-network paths

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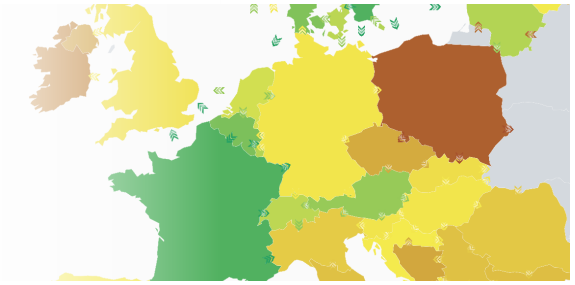
Carbon intensity of network with respect to interface pair



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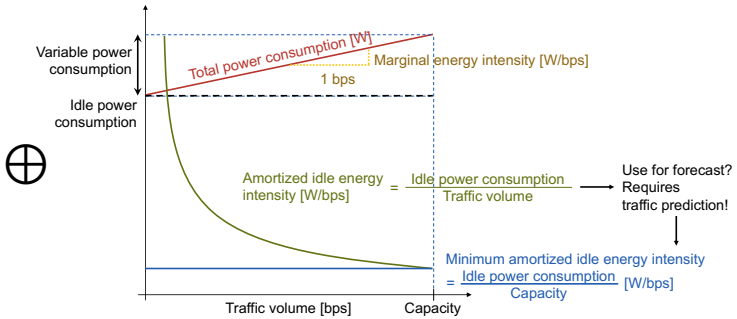

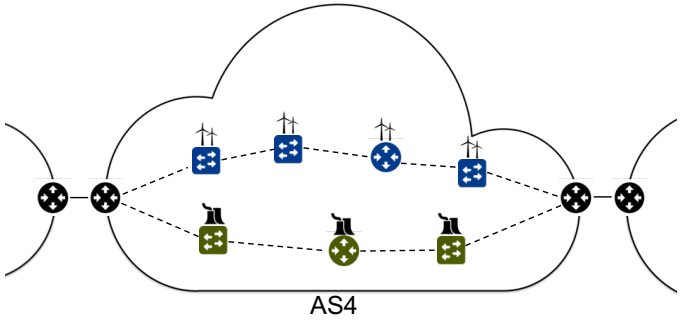

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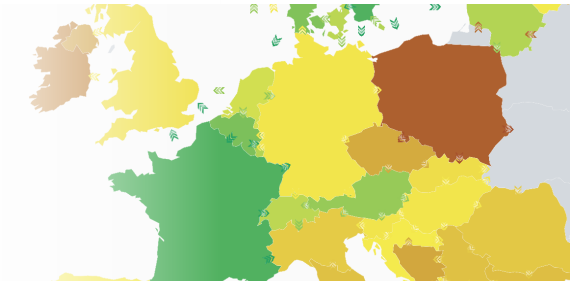
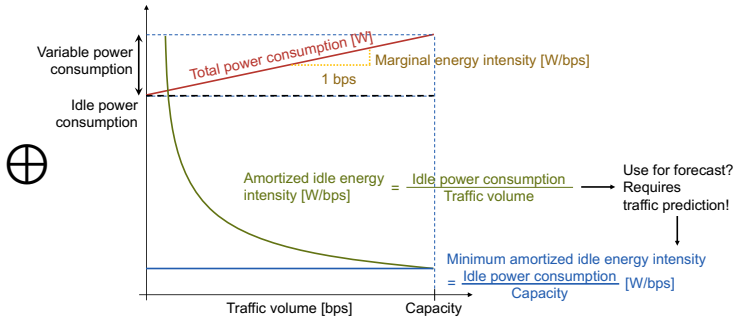
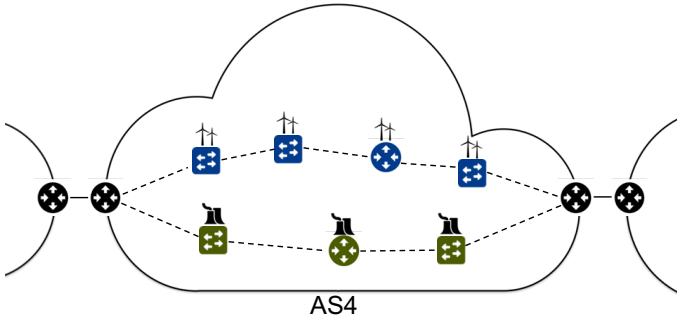
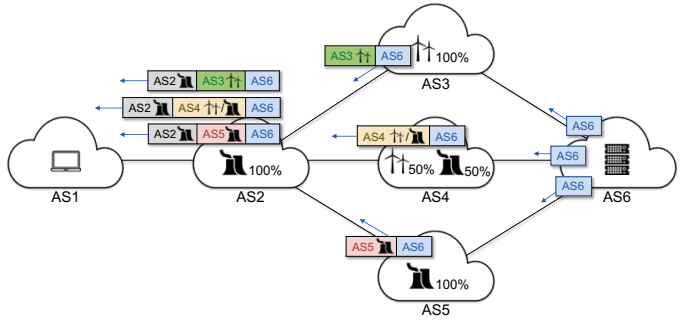
Carbon intensity of Internet path









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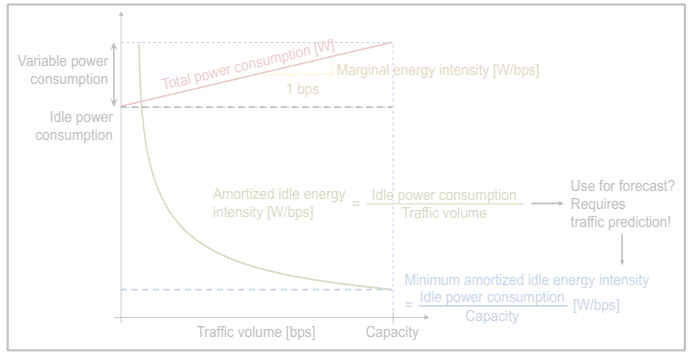

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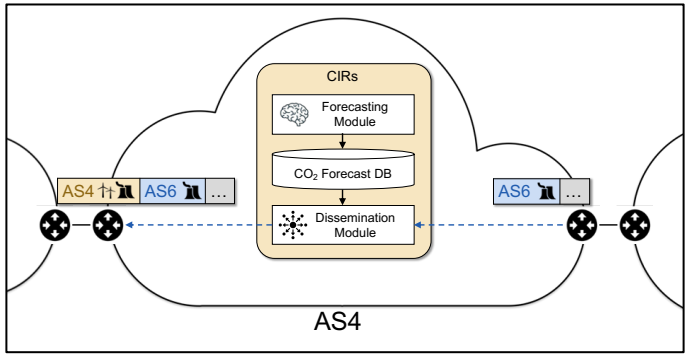

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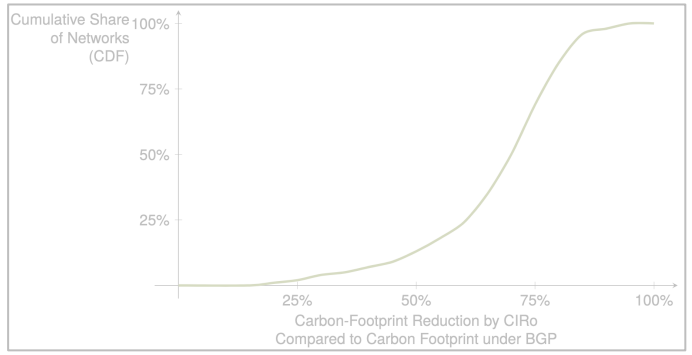

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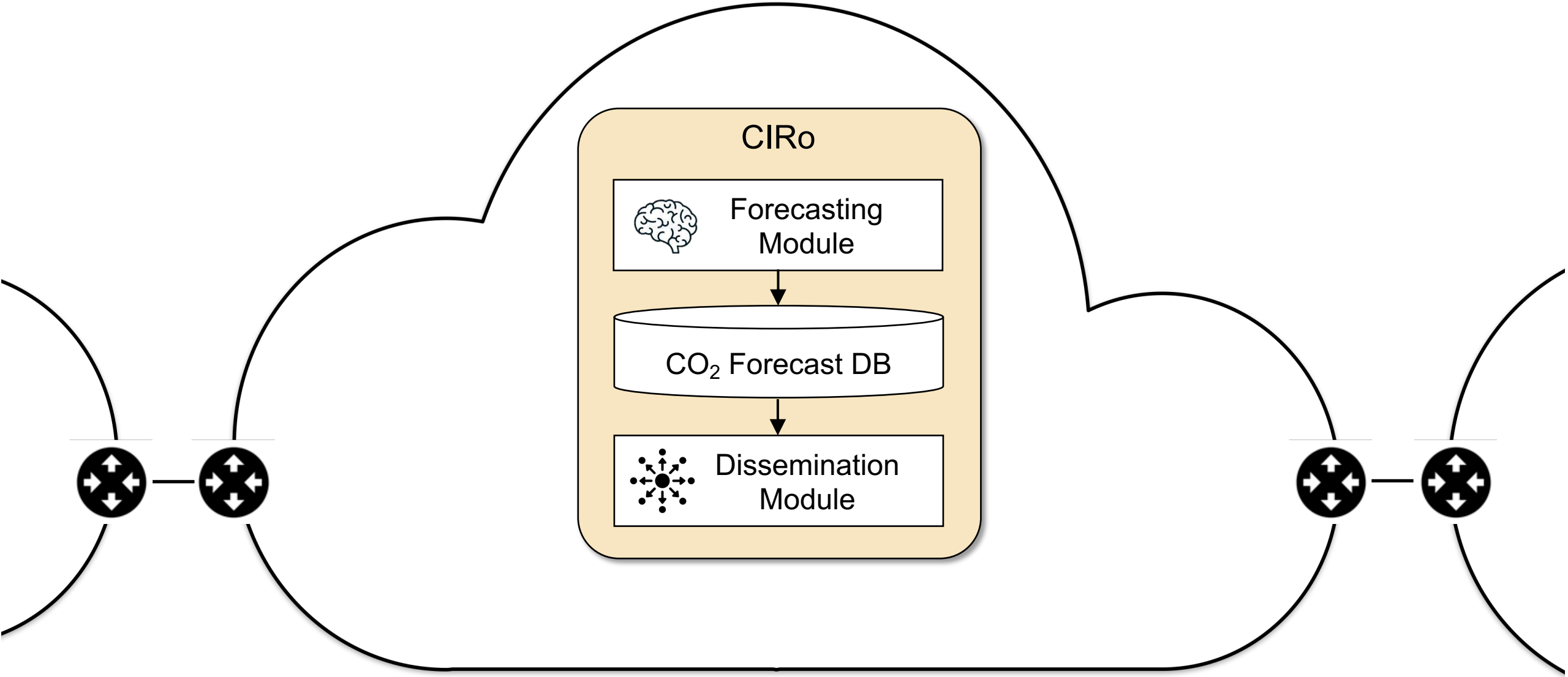

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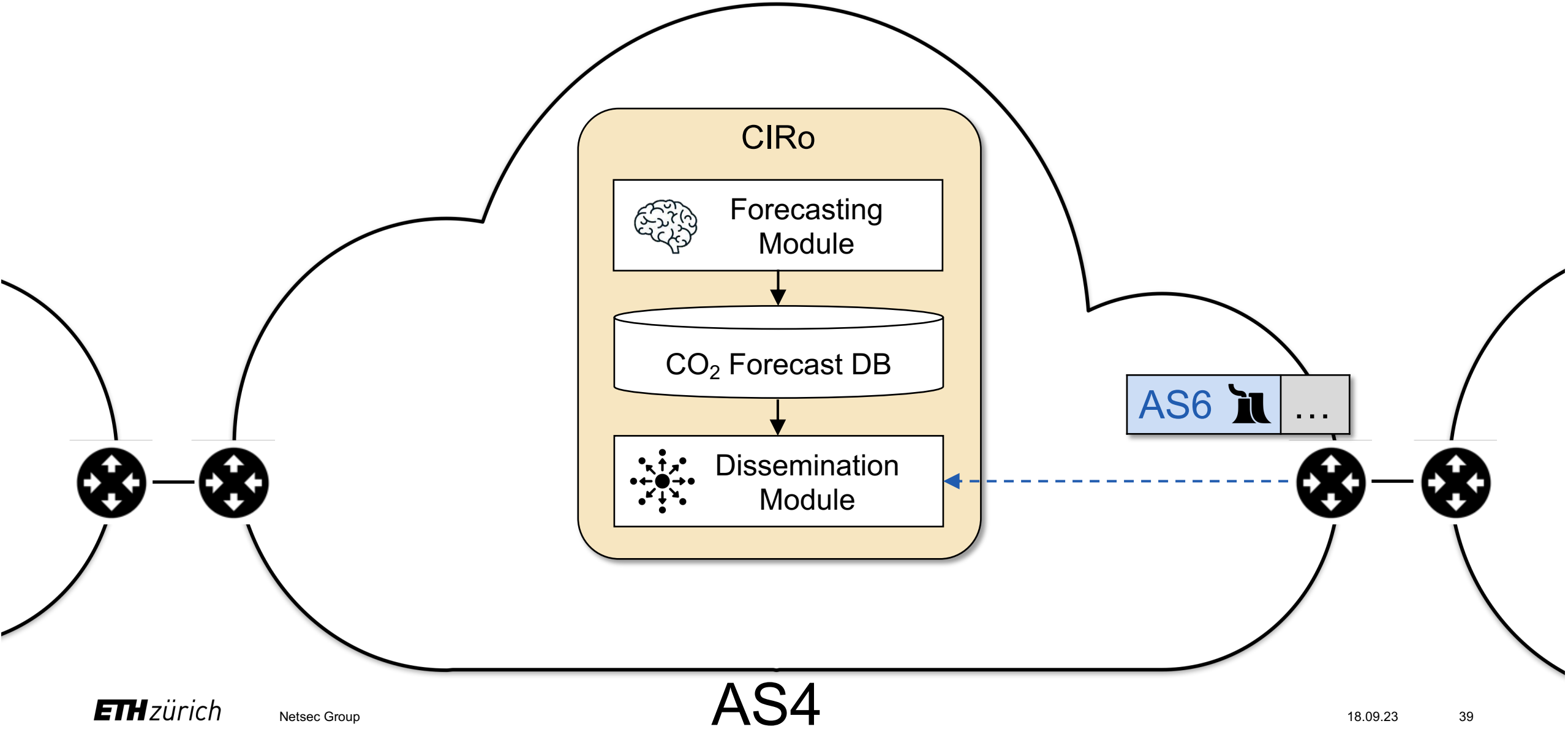

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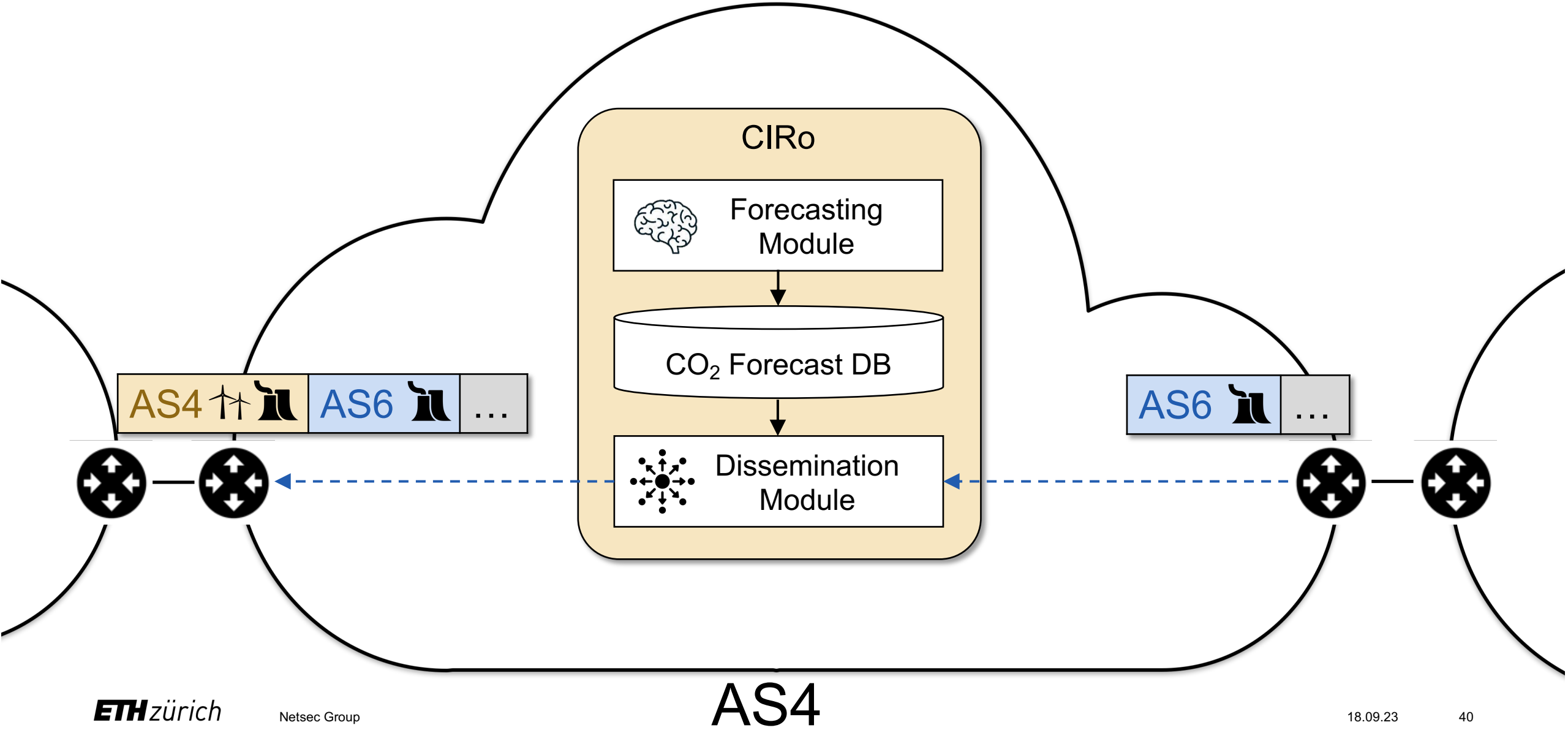

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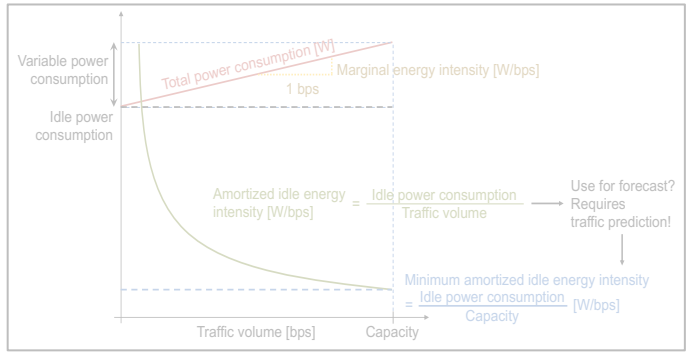

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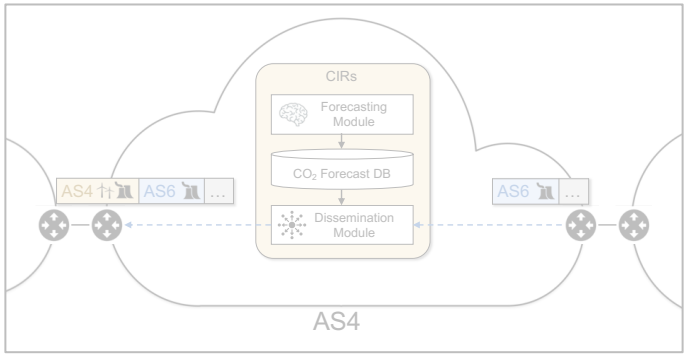
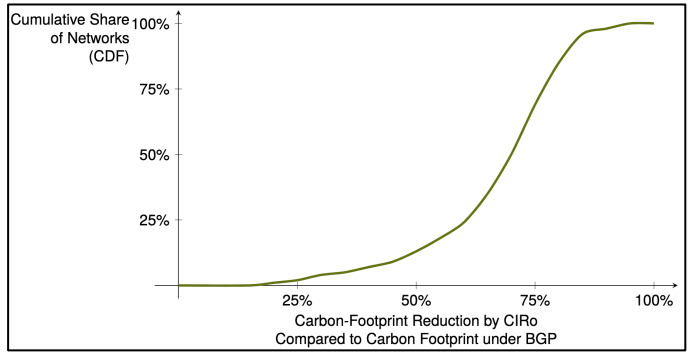
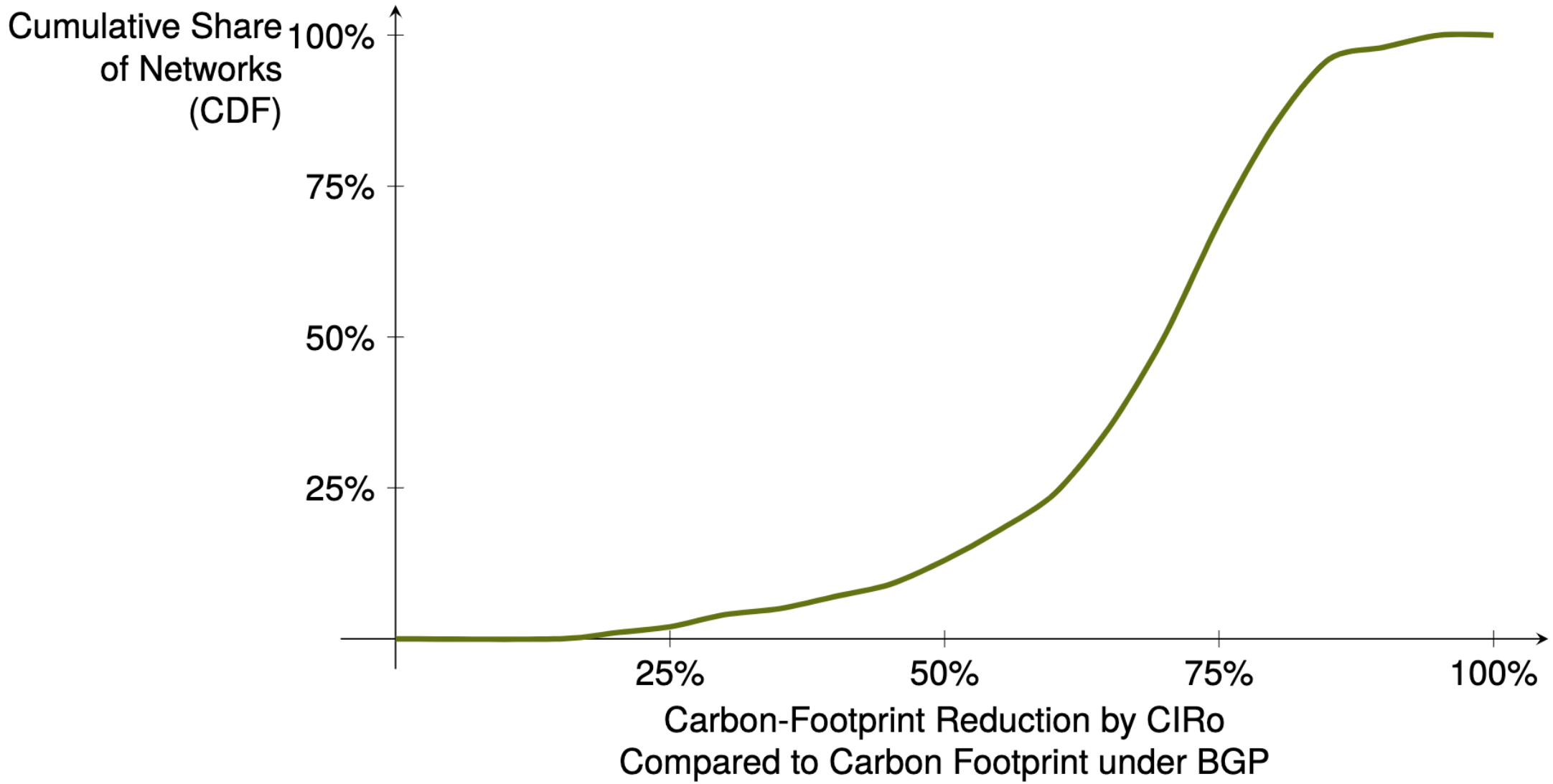


Carbon-Footprint Impact Analysis

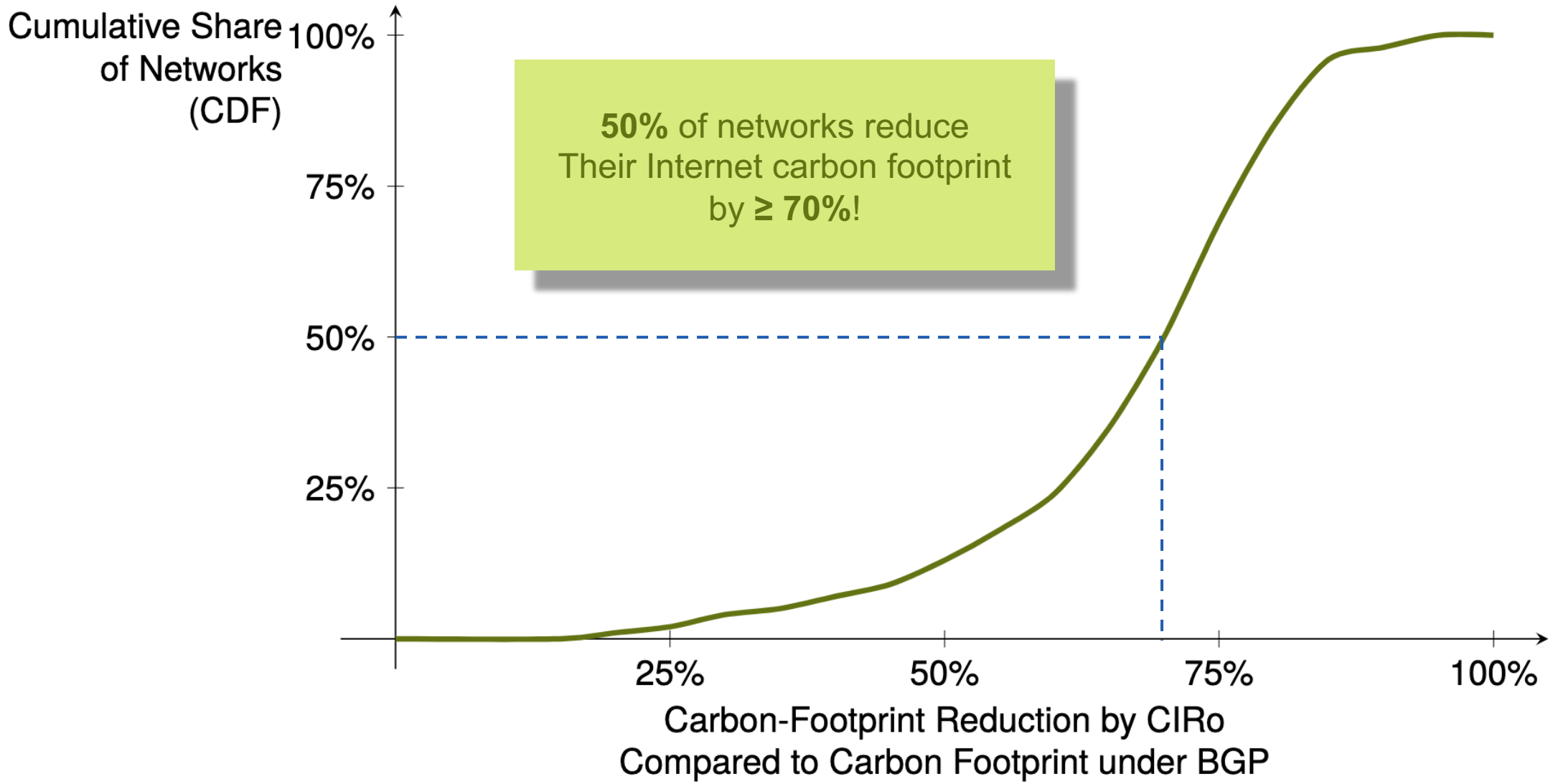
Simulation on data-backed large-scale topology



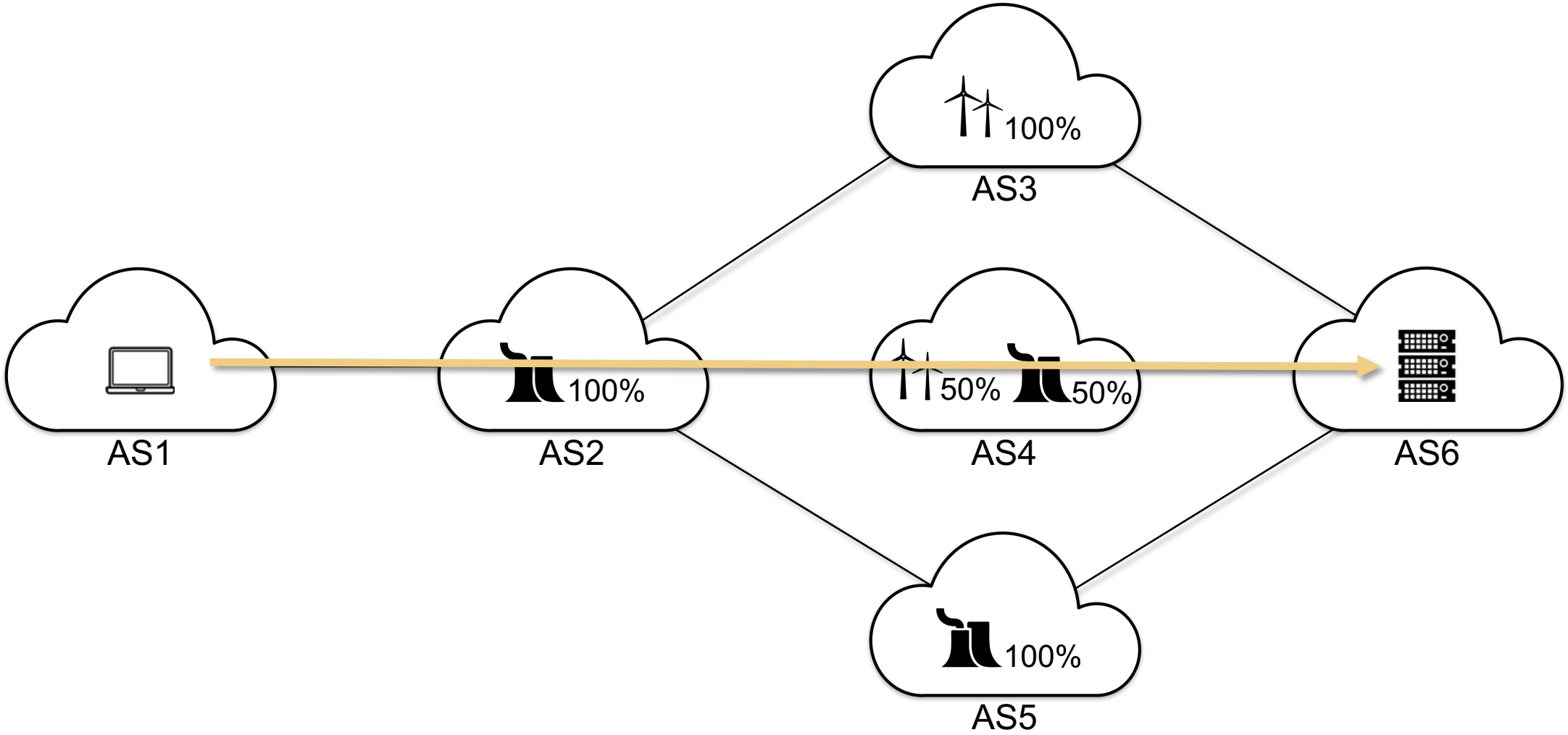
Carbon Footprint Simulation (CAIDA Core Topology)



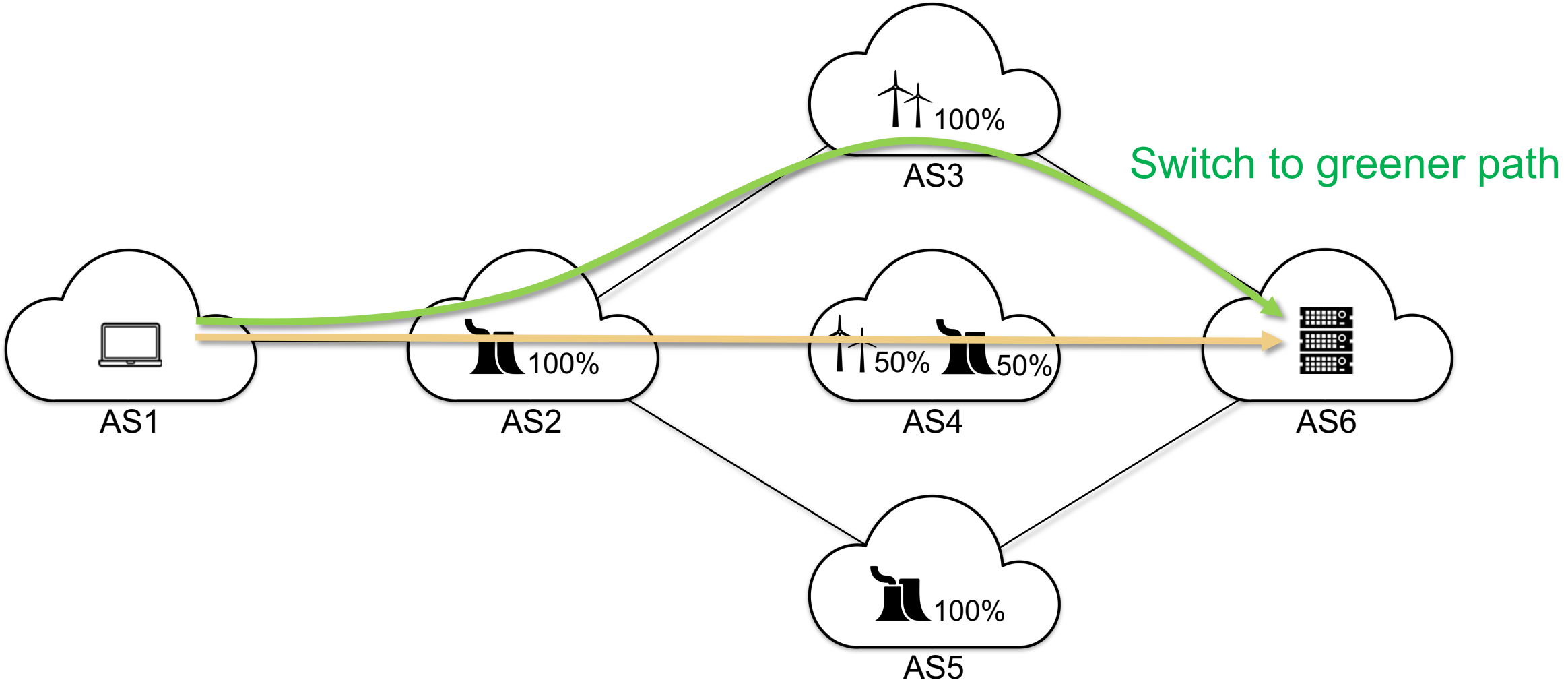
Carbon Footprint Simulation (CAIDA Core Topology)



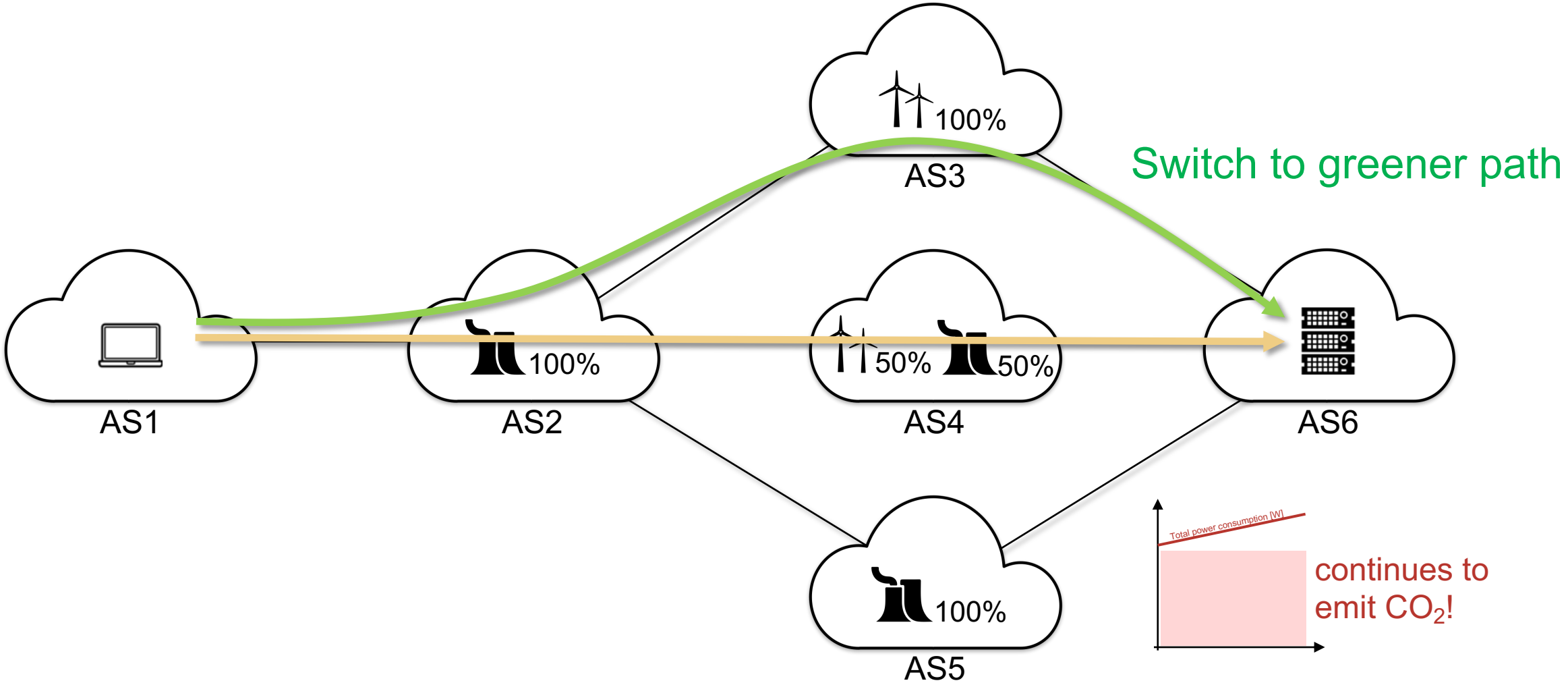
Carbon Footprint ≠ Carbon Emission



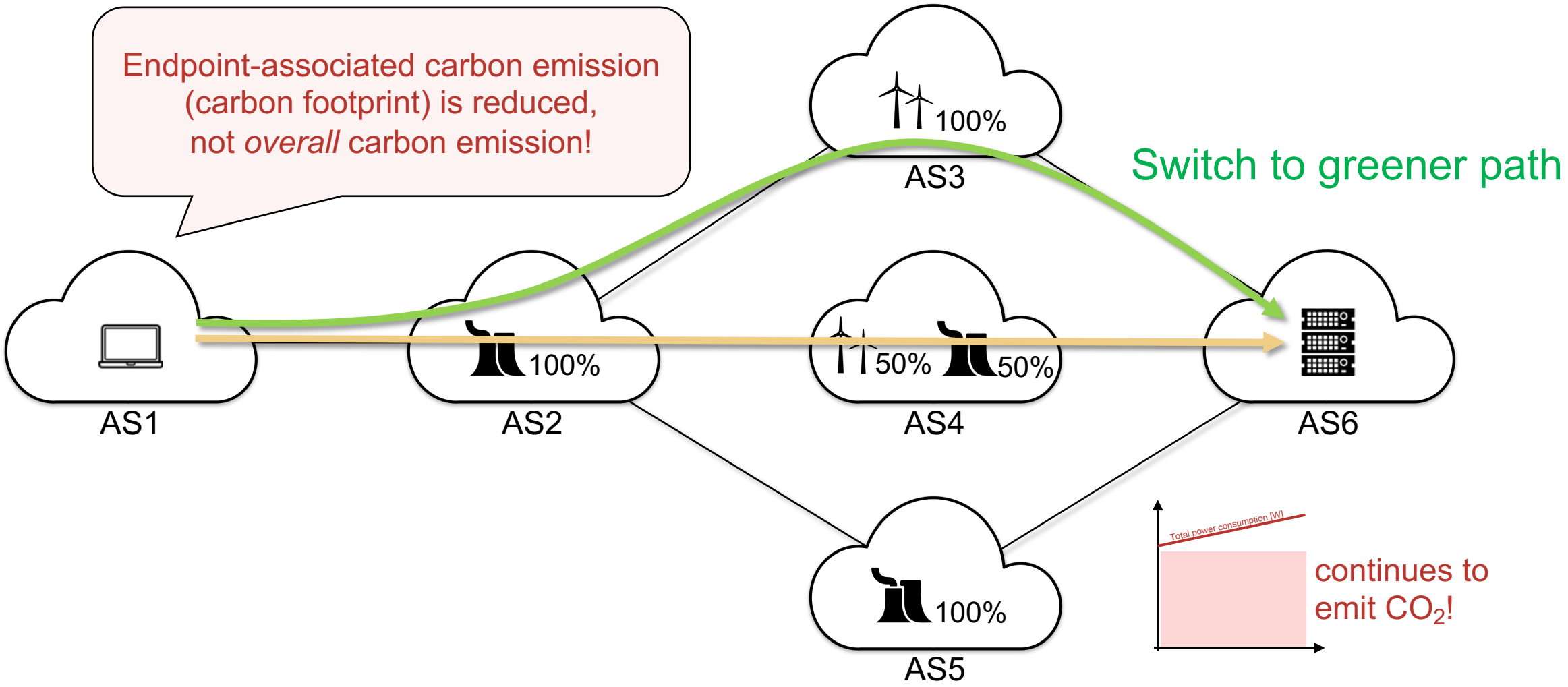
Carbon Footprint ≠ Carbon Emission



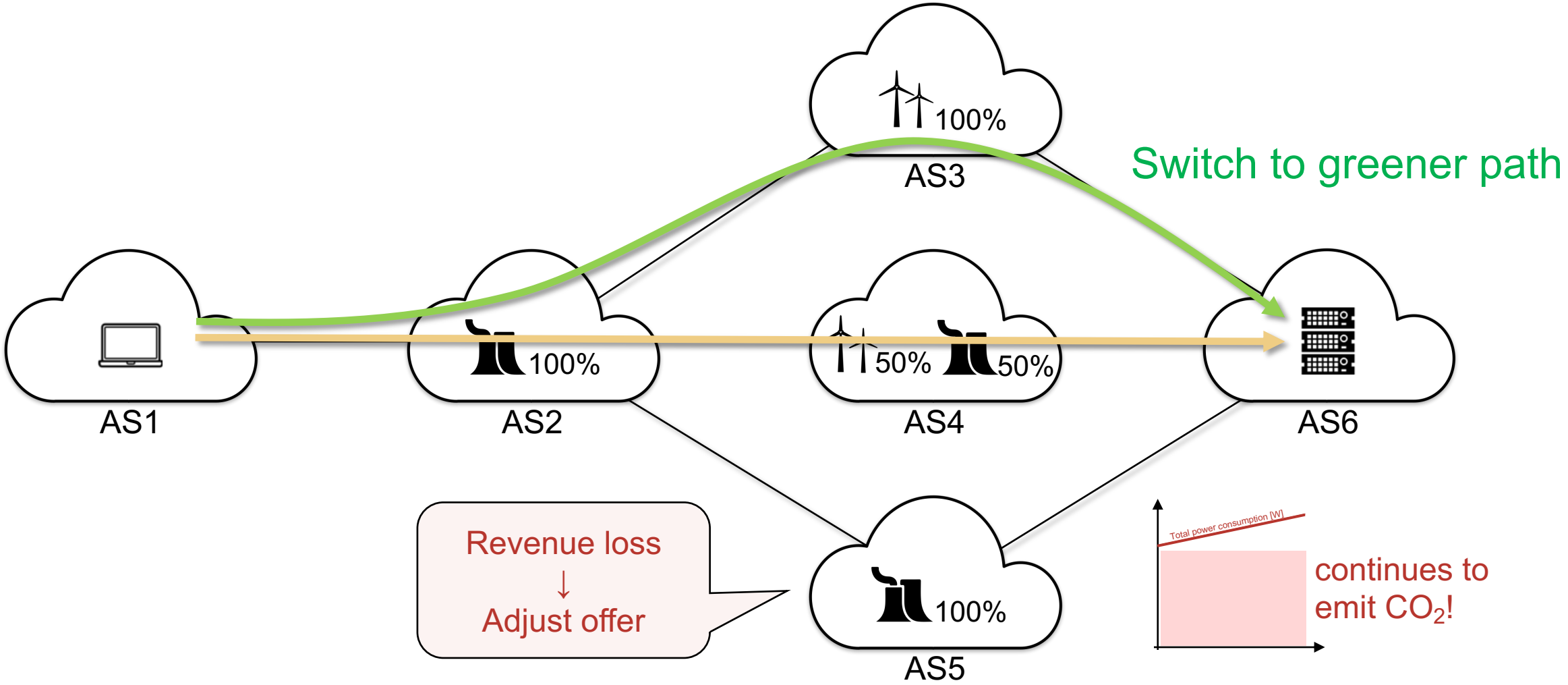
Carbon Footprint ≠ Carbon Emission



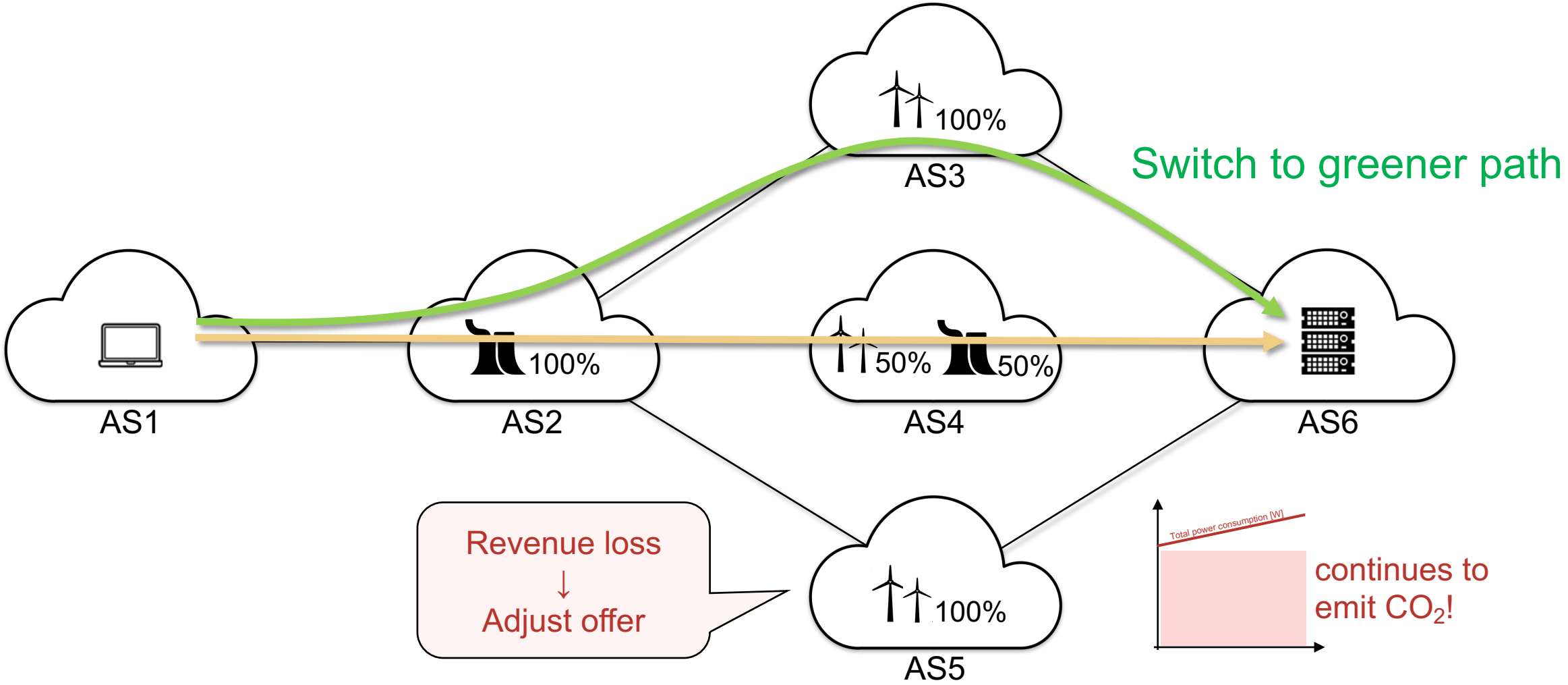
Carbon Footprint ≠ Carbon Emission



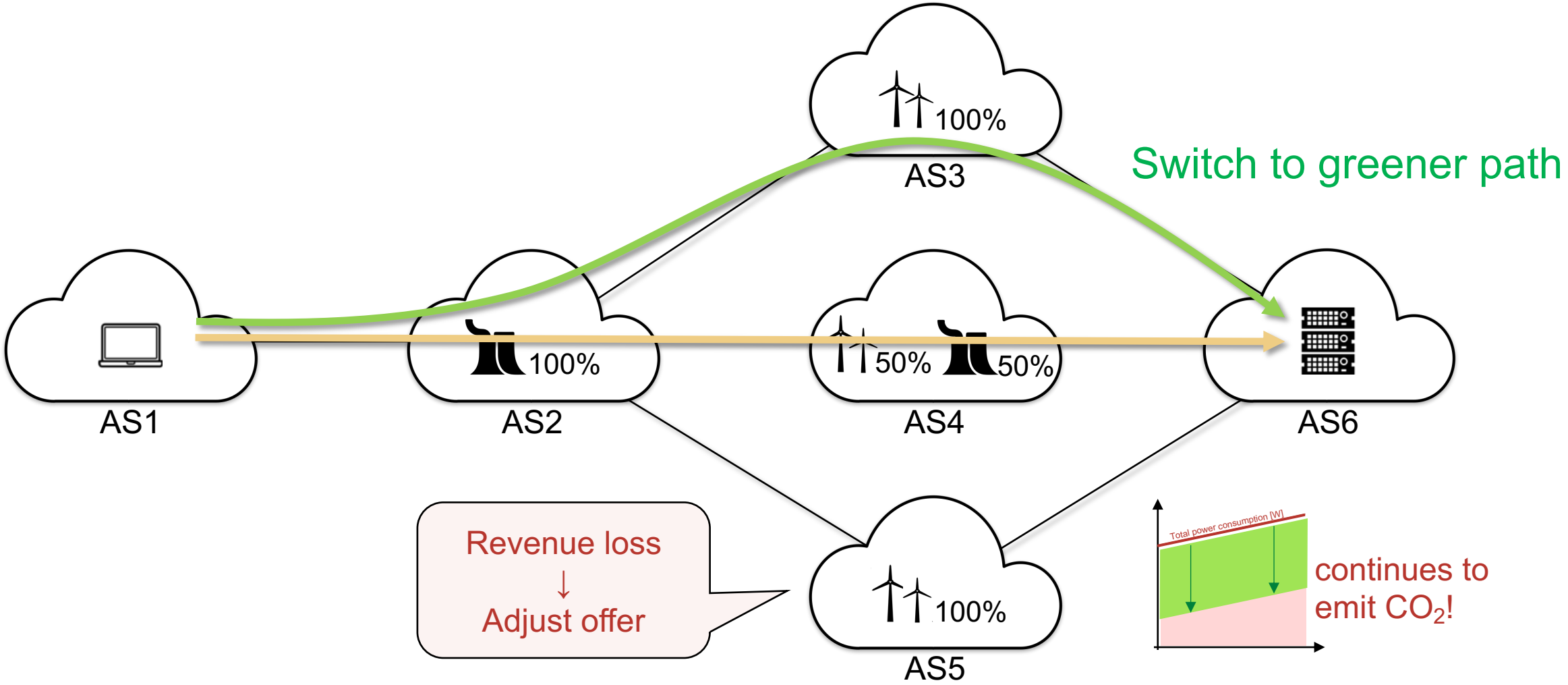
How to Actually Reduce Emission?



How to Actually Reduce Emission?



How to Actually Reduce Emission?



Carbon-Aware Global Routing in Path-Aware Networks

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ABSTRACT

The growing energy consumption of Information and Communication Technology (ICT) has raised concerns about its environmental impact. However, the carbon footprint of data transmission over the Internet has so far received relatively modest attention. This carbon footprint can be reduced by sending traffic over carbon-efficient inter-domain paths. However, challenges in estimating and disseminating carbon intensity of inter-domain paths have prevented carbon-aware path selection from becoming a reality.

In this paper, we take advantage of path-aware network architectures to overcome these challenges. In particular, we design CIRo, a system for forecasting the carbon intensity of inter-domain paths and disseminating them across the Internet. We implement a proof of concept for CIRo on the codebase of the SCION path-aware Internet architecture and test it on the SCIONLab global research testbed. Further, through large-scale simulations, we demonstrate the potential of CIRo for reducing the carbon footprint of endpoints and end domains: With CIRo, half of domain pairs can reduce the carbon intensity of their inter-domain traffic by at least 47%, and 87% of end domains can reduce their carbon footprint of Internet use by at least 50%.

CCS CONCEPTS

• **Applied computing** → **Forecasting**; **Multi-criterion optimization and decision-making**; • **Networks** → **Network measurement**; **Network simulations**; **Network performance modeling**; **Data path algorithms**; **Control path algorithms**; Topology analysis and generation; • **Hardware** → **Renewable energy**.

KEYWORDS

Green Networking, Internet Carbon-Emission Modeling and Measurement, Inter-Domain Routing, Carbon-Aware Routing, SCION

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1 INTRODUCTION

Growing concerns regarding climate change encourage companies to measure and reduce their carbon footprint, i.e., the amount of carbon emission that can be attributed to them. This also applies to their use of Information and Communication Technology (ICT), as ICT has a notable contribution of 2.7% to global CO_2 emissions [39], which is expected to grow significantly – approximately four times – until 2030 [3]. Hence, reducing the carbon footprint of ICT use is becoming increasingly relevant for enterprises, manifesting in carbon-neutrality statements of major technology corporations.

While these efforts are laudable and impactful, promising opportunities for further carbon-footprint reduction exist. Indeed, previous research has identified a range of such opportunities. However, most of these proposals apply to local aspects: intra-domain networking (i.e., within a single domain), data-center optimizations, or neighbor-domain cooperation (cf. §8). In contrast, inter-domain networking (i.e., among multiple domains), which accounts for around 13% of total ICT energy consumption, has so far received less attention. An exception is the work by Zilberman et al. [70] who identify carbon-aware networking as a high-potential resear area and sketch the concept of carbon-intelligent routing, i.e leverage differences in network paths' carbon intensity (i.e bon emission per unit of data transmitted) to reduce the footprint of communications.

Previous research on green inter-domain networki carbon efficiency to the optimization metric of the B way Protocol (BGP) [42]. Unfortunately, this direction challenges. **Inefficient Green Route**: A strict carb can result in a highly inefficient end-to-end path tary cost, latency, bandwidth, loss, or jitter (cf. the application requirements, an optimizati constraints needs to be made, requiring fine-grained metric space. **Ossification**: thus only be offered as additional opt the conventional BGP route. Whe efficient alternative paths, route warding tables, and packets optimization criteria. Upd sents a challenge – as

More in the Paper

Carbon Intensity Modeling

Inter-Domain CIDT
Per-Hop CIDT
Single Path CIDT

Detailed System Design

Forecasting Module
Dissemination Module
Header Design

Evaluation

SCION vs. BGP
Carbon intensity vs. Latency

Summary

The first Internet-wide carbon footprint monitoring system

Enabling endpoints to select the greenest paths

Introduces green competition between ISPs

Expected savings: 20% CO_2 reduction for global ISPs

Q&A

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