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On the Economic Benefits of Software-Defined Networking and Network Slicing for Smart Grid Communications

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Abstract To ensure stable operation, Smart Grids rely on ultra-reliable, low latency communications for transmitting critical measurements and control commands. Though modern Information and Communication Technology (ICT) provides adequate means for asserting hard service guarantees, the installation, configuration and operation of corresponding infrastructures is typically very costly, involving significant administration efforts. Therefore, we propose Software-Defined Networking (SDN) to facilitate configuration and administration drastically, thus reducing expenditures. We identify technical advantages of introducing this approach to Smart Grid communication infrastructures and derive economic benefits. Numerical results for a reference power system indicate Operational Expenditures (OPEX)-driven savings that allow SDN solutions to outperform legacy networks within less than four years. Also, SDN-driven network slicing enables sharing infrastructures between critical power system and end consumer broadband traffic, allowing for further cost reductions, while maintaining hard service guarantees. Under this paradigm, we compare the installation and operation of dedicated infrastructure by the grid operator to arranging service contracts with telecommunication network operators. This is referred to as *make* or *buy* decision. It can be deduced that a shared infrastructure, building on network slicing, provides an optimal solution for both parties.

Keywords Techno-Economics · Smart Grid Communications · Software-Defined Networking · Network Slicing · Network Operator Models

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1 Introduction

Driven by the aim to reduce greenhouse gas emissions, the energy sector experiences massive change, including the shift towards renewable and distributed generation, the introduction of Electric Vehicles (EVs) and the liberalization of energy markets [18]. However, these developments involve fluctuating, bidirectional power flows, which endanger power grid stability. To prevent cascading outages or even complete black-outs, real-time monitoring and control become increasingly important. Hence, ultra-reliable, low-latency ICT infrastructures are required, which are able to serve the diverse demands of numerous applications. Accordingly, adequate means of communication become a major requirement for future power systems [58].

Building upon the separation of the communication network's data and control plane, SDN presents a conclusive solution for this issue. In this context, Open Flow (OF) [34] is established as the most prominent protocol for the interface between these planes. Additionally, the SDN Northbound Interface (NBI) allows applications to interact with the control plane, enabling network configuration according to their requirements. By integrating and combining multiple, different approaches, SDN facilitates ensuring hard service guarantees. In combination with Network Function Virtualization (NFV) [17], SDN offers relevant opportunities to reduce Operational Expenditures (OPEX). Subsequently, it is a promising candidate for providing technologically advanced, cost-efficient Smart Grid communications. Today, SDN is already deployed successfully on the Wide Area Network (WAN) level by major ICT companies such as Facebook or Google [24].

In previous studies we performed in depth analyses of SDN's technical feasibility for power system communications [13, 15, 16], whereas this paper focuses on the techno-economic evaluation of installing and operating such networks. In particular, we contrast SDN-based with *legacy* communication networks for both greenfield and brownfield scenarios. Moreover, we study different operator models from a power grid operator's point-of-view (referred to as *utility*). We compare the set-up of dedicated infrastructure by the utility (*make* decision), including the lease of excess capacity to third parties, to purchasing communication as a service (*buy* decision) from telecommunication network operators (*telcos*). Here, SDN enables the shared use of cellular infrastructures for distribution grid communications in terms of virtual overlay networks. This approach is referred to as network slicing and considered a fundamental part of 5th Generation Mobile Networks (5G) [1, 33]. In this context, network slicing offers strict service isolation, enabling hard service guarantees and enhanced security [1, 21, 26].
The main contributions of this work are:

- the development of a techno-economic model for SDN-enabled Smart Grid communications
- case studies, evaluating the ideal balance between dedicated and shared, network slicing-based, ICT infrastructures for distribution and transmission power systems

The remainder of this paper is structured as follows: Section 2.1 reviews related work. In Section 2.2 we provide an overview of SDN and detail its benefits for Smart Grid communications. Next, our techno-economic modeling approach is introduced in Section 3. Sections 4 and 5 comprise scenario descriptions and evaluation results for an SDN-based transmission system network as well as for a shared distribution and transmission grid communication infrastructure. The paper is completed by a conclusion and an outlook on future work in Section 6.

2 State-of-the-Art on Techno-Economic Evaluations of Software-Defined Networking

Typically, techno-economic modeling involves defining scenarios, analyzing technical constraints and properties as well as deducing associated costs. For evaluation, we utilize the following common parameters:

– Total Cost of Ownership (TCO), defined as the aggregate expenditures during the complete evaluation period T:

$$TCO = \sum^{t \in T} CAPEX_t + OPEX_t \tag{1}$$

– Net Present Value (NPV), being the discounted cash flows of all periods t, using discount rate i:

$$NPV = \sum^{t \in T} \frac{CF_t}{(1+i)^t} \tag{2}$$

It needs to be stressed that - deviating from the common definition - NPV is specified from the cost perspective here. Subsequent sections detail related work on techno-economic modeling of communication systems and introduce the economic benefits of SDN.

2.1 Related Work on Techno-Economic Evaluations of Communication Systems

There is a rich literature body on the technical feasibility of SDN in general, but also on solutions tailored to Smart Grid communications. Sydney et al. introduced SDN to power system communication infrastructures and conducted a simulative comparison to Multi Protocol Label Switching (MPLS) [47]. Substation network configuration is realized with the help of SDN in [8]. In [7] SDN-based concepts for achieving resilience in distribution grid communications are presented and evaluated. OF is employed for multicast fault tolerance in power system ICT infrastructures in [41].

Also, numerous studies deal with the techno-economic evaluation of communication infrastructures. Yet, these papers mainly focus on end-consumer broadband access, especially next generation fiber networks. Machuca *et al.*

[31] and Mahloo *et al.* [32] determine the TCO of reliable access networks. In [56] different architectures for survivable optical access networks are compared with regard to availability, energy consumption and costs. Migration strategies for active optical networks and their economic impact are studied in [55]. A cost model for multilayer communication nodes in optical metro and core networks is developed in [43]. Romero Reyes *et al.* [44] propose a bottom-up framework for allocating TCO to services in communication infrastructures, distinguishing direct, shared and common cost components. The approach is illustrated on a case study of transport services for flex-grid optical networks.

Significantly less attention has been paid to the economics of power system ICT infrastructures. A combined solution of fiber and wireless networks, shared between end-consumer broadband access and Smart Grids, is analyzed in [9].

Similarly, only few authors deal with the impact of SDN on the economics of communication networks. A fine grained analysis of NFV/SDN implications on the OPEX of network service providers is presented in [22]. However, the study does provide neither an application example nor numerical results. In contrast, Naudts *et al.* [37] provide evaluation results for an SDN-based backbone of mobile broadband access networks, yet focus on the Capital Expenditures (CAPEX) side.

Our paper continues the work of [14], significantly improving on its modeling approach and considering the impact of SDN/NFV. To the best of our knowledge, this is the first work to provide a detailed evaluation of the TCO for an SDN infrastructure, presenting numerical results for a reference power system.

2.2 Economic Implications of Software-Defined Networking

The separation of data and control plane can be described as the main idea of SDN. On basis of this concept, network elements, such as routers or switches, are reduced to their forwarding functionality. Control logic, on the other hand, is extracted and concentrated at a central instance. This so-called SDN controller can be implemented either as a single, programmable platform, a cluster or a hierarchy of controllers. Taking advantage of its global network view, the controller is able to determine network behavior dynamically by establishing and modifying forwarding rules at the network devices [28]. Deploying SDN in Smart Grids allows applications to convey their specific requirements and influence network configuration [15]. Figure 1 provides an overview of the most relevant benefits of SDN and their economic implications, which are detailed below.

2.2.1 Energy Savings

Exploiting flexible configuration capabilities, forwarding elements may be switched on and off dynamically, as shown in [30, 36]. Temporary shutdown of components helps minimizing power consumption, enabling OPEX savings.

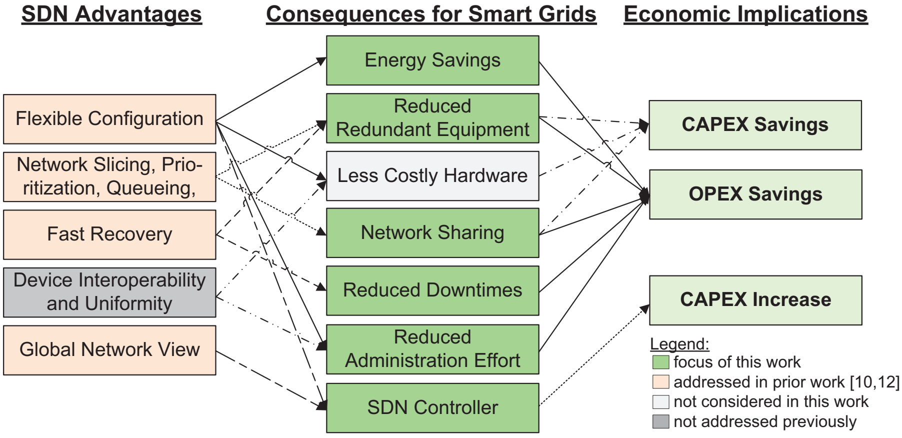

Fig. 1 Causal connection between the advantages of SDN and corresponding economic implications on Smart Grid systems

In addition, device consolidation and simplification play an important role in reducing energy consumption [22].

2.2.2 Reduced Equipment Redundancy

Fast recovery [16, 48] and traffic engineering [15, 35] enable an optimized network architecture with regard to redundancy provision. In SDN environments, a limited number of back-up paths is sufficient to ensure communication reliability, whereas legacy networks of critical infrastructures require full redundancy to compensate failures. SDN's advantage is a result of introducing automated methods of handling failures, recovering traffic to alternative paths within a few milliseconds. A detailed analysis on the technical realization of SDN data plane reliability in the context of Smart Grid communications has been performed in [16].
The global view of the SDN controller enables improved network utilization on basis of traffic engineering and load balancing. Thus, significant overprovisioning of network capacities becomes unnecessary [37]. This benefit is verified by Google's Software-Defined WAN achieving near 100 % utilization [24]. Subsequently, CAPEX for network equipment are reduced, affecting OPEX for operation, maintenance and repair as these scale with the number of devices.

2.2.3 Less Costly Hardware

Improved device interoperability precludes vendor lock-in [59], thereby diminishing costs for active components. Also, SDN decreases network element variety [23], enabling economies of scale. Both factors lead to CAPEX reductions.

2.2.4 Network Slicing / Sharing

One of the most promising benefits of SDN - in combination with NFV - is the opportunity to establish multiple, isolated virtual overlay networks, tailored to the demands of individual applications, while using the same physical hardware [23]. This approach is commonly referred to as network slicing and applied as part of 5G standardization [1, 33]. Following this concept, each communication service is assigned to a defined network slice, which is separated from other slices in order to provide hard service guarantees. Prioritization and queuing, configured and managed via software, are the foremost enablers of this network sharing. Hence, instead of creating costly, dedicated networks for critical power systems, their traffic can be handled via slices of one unified, cost-efficient, physical network [2]. On this basis, massive CAPEX and OPEX savings may be realized. In addition, network slicing improves communication reliability and security. An increased level of security can be obtained directly from utilizing isolated network resources, which ensure that compromised slices do not affect others. For example the authors of [26] propose a secure network slicing approach on basis of SDN and NFV. There are no additional expenses, incurred by this measure, as it is a fundamental part of the architecture itself [21].

2.2.5 Reduced Downtimes due to Increased Network Resilience

In general, network failures can be categorized as software or hardware induced. The hardware itself is not likely to become more reliable due to the introduction of SDN. However, as a consequence of increased interoperability and leaner devices the number of failures is expected to decrease due to comprehensive knowledge of the employed hardware [22]. Also, improved monitoring capabilities are established on basis of the SDN controller's global network view. This allows for preventive replacement of equipment, likewise limiting unplanned outages [37].
The handling of software faults is eased by SDN's centralized approach as well. Enhanced reliability features reduce the frequency and urgency of field repairs as more failures can be handled via remote software intervention [57]. Finally, with the help of prioritization and fast recovery mechanisms penalties for noncompliance to service guarantees can be minimized. All of these aspects enable considerable OPEX reductions.

2.2.6 Reduced Administration Effort

Flexible configuration, improved device interoperability and uniformity allow OPEX savings based on reduced administration staff size. SDN enables automated, global network configuration, limiting the demand for manual intervention [57]. Standardization of networking elements reduces the variety of software solutions deployed for infrastructure administration [37]. This applies for security management systems as well.

2.2.7 Software-Defined Networking Controller

The concept of SDN relies on the centralization of network control capabilities at a corresponding controller [34]. This directly involves CAPEX for the controller hardware as well as for software development. Typically, most controller architectures include certain security and reliability provisions already [4]. SDN's open source approach furthers the development of reliable and secure solutions due to being tested by numerous developers (volunteers). It is even becoming standard industry practice [38, 39]. For example, the controller has to support fast recovery approaches for handling data plane failures, as outlined in Subsection 2.2.2. With regard to security, authentication needs to be established between the controller, switches and applications [46]. Besides, several existing security approaches, such as firewalls or intrusion detection systems, may capitalize on the controller's global view of network behavior [46]. Expenses for integrating such mechanisms are considered as part of SDN controller software development.
In addition, secure and reliable operation of the SDN control plane itself has to be guaranteed. For this purpose, we consider communication architectures, steered by multiple controllers (two at minimum). Different concepts of controller interaction and resilience are discussed in [29]. Corresponding costs are accounted for in terms of software development efforts and additional controller hardware.

3 Proposed Techno-Economic Modeling Approach

This section details the different elements of our techno-economic evaluation approach, which are Smart Grid traffic modeling, network dimensioning, operator modeling and cost modeling. An overview of these elements, their components and interdependencies between them is shown in Figure 2.

3.1 Smart Grid Traffic Modeling

We distinguish three types of traffic, transmission grid, distribution grid and end consumer broadband communications, which are detailed in the following.

3.1.1 Transmission Grid Communications

Traffic in the transmission power grid is modeled on basis of the International Electrotechnical Commission's (IEC) standard 61850, which is well-established for substation automation. It has been extended to further power system domains, such as Wide-Area Monitoring Protection and Control (WAMPAC) and Distributed Energy Resource (DER) connection. Substation automation comprises Sampled Value (SV) and Generic Object Oriented Substation Event (GOOSE) services for transmitting measurement values respectively switching commands. Substation Local Area Networks (LANs) are modeled using

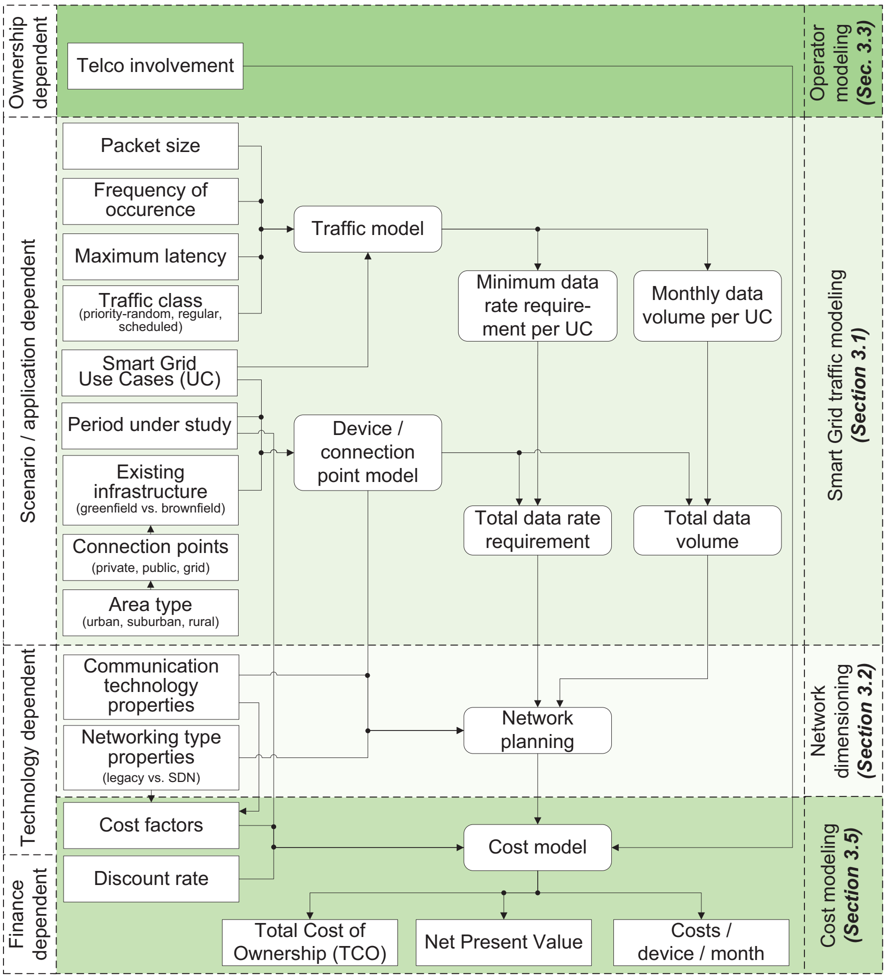

Fig. 2 Techno-economic modeling framework for Smart Grid communication networks

fiber-optics. Hence, transmission capacities are considered sufficient even for extremely frequent SV transfers with intervals of 250 μs. For wide-area inter-substation protection we consider regular exchange of SV messages (122 Byte) between adjacent substations every 1 ms. Furthermore, GOOSE messaging (159 Byte) is used to provide status updates from all substations to the control center - as part of a Supervisory Control and Data Acquisition (SCADA) system - and vice versa for remote control with an Inter-Arrival Time (IAT) of 1 s. In the SDN case these messages can be transmitted directly, whereas on legacy infrastructures tunneling is required. The cumulated network data rate amounts to 368 Mbps.

Table 1 Excerpt of communication services and associated parameters, mapped to smart distribution grid use cases, with values derived from [19]

Service	**Packet size (brutto) [kByte]**	**Max. allowed latency [s]**	**Minimum data rate per Smart Grid device [bps]**	**Traffic Class**	**Direction**	**AMR**	**DG/DS**	**DA**	**DSM**
Time synchronization	1.2	18	533	c_r	DL/UL	X	X	X	X
Firmware upgrade	10,800.0	172,800	500	c_s	DL	X	X	X	X
Profile management	4.5	60	600	c_s	DL	X	X		X
Monitoring system log	120.0	300	3,200	c_s	UL	X			X
Metering values	2.1	900	19	c_r	UL	X			
DG/DS command	2.0	30	533	c_p	DL/UL		X		
EV fleet management	5.0	60	667	c_p	DL		X		
Grid state monitoring	2.4	5	3,840	c_r	UL			X	
DSM command	1.8	10	1,440	c_p	DL/UL				X

3.1.2 Distribution Grid Communications

For assessing communications in the distribution power grid, we determine minimum data rate requirements per connection point. Communication is classified into four different use cases: Automated Meter Reading (AMR), Distributed Generation and Storage (DG/DS), Distribution Automation (DA) and Demand Side Management (DSM). Each use case encompasses several communication services, specifying individual sets of traffic demands, including packet size p (complemented by protocol and security overheads), IAT, maximum allowed latency T and service class c, derived on the basis of [19]. The minimum data rate requirement per service is defined as the quotient of packet size and maximum allowed latency. With regard to service classes, we differentiate between *priority-random* (c_p), *regular* (c_r) and *scheduled* (c_s) transmissions. Combining these properties, minimum data rate requirements R_{min} per use case and transmission direction (up-/downlink) can be derived, as given in Equation 3,

Table 2 Mapping of smart distribution grid use cases to connection point types and increase in traffic volume (*NA = Not Applicable*)

Smart Grid Use Cases	**Year**	**Traffic Factor per Connection Point**		
		Private	Public	Grid
Advanced Meter Reading	2018	1	*NA*	*NA*
	2048	1	*NA*	*NA*
Distributed Generation / Storage	2018	1	5	*NA*
	2048	3	20	*NA*
Distribution Automation	2018	*NA*	*NA*	1
	2048	*NA*	*NA*	1
Demand Side Management	2018	0	1	*NA*
	2048	1	15	*NA*

$$R_{min} = \sum^{\forall i|c_i=c_p} \frac{p_i}{T_i} + \sum^{\forall i|c_i=c_r} \frac{p_i}{T_i} + \max^{\forall i|c_i=c_s} \left(\frac{p_i}{T_i}\right), \tag{3}$$

where c_i is the service class of service i. In a worst case scenario, all prioritized services happen to occur at the same instant. Therefore, minimum date requirements of all such services are aggregated. Also, data rates of regular services are summed up, since the allowed latencies of these services typically equal respective IATs, constituting a kind of base load on the network. In contrast, scheduled services may be shifted in time flexibly so that - even for worst case modeling - only the most challenging of these services needs to be considered.

Table 1 lists an excerpt of the most relevant communication services with their corresponding parameters. In addition, a mapping to respective smart distribution grid use cases is provided. Some of the services cover comprehensive tasks such as regular time synchronization or schedulable firmware upgrades. Hence, they are part of every use case. In contrast, other services are applied for specific distribution grid use cases only. For example, regular metering value transmissions are performed as part of the AMR use case only, whereas prioritized EV fleet management is limited to the DG/DS use case.

Next, use case requirements are translated to connection point demands. These connection points represent the actual communication end devices and

Table 3 Resulting aggregated data rate requirements per connection point in downlink and uplink direction, based on combining values from Tables 1 and 2

Year	**Aggregated Data Rate per Connection Point [kbps]**					
	Private		Public		Grid	
	DL	UL	DL	UL	DL	UL
2018	4.1	5.1	16.1	11.3	1.1	4.8
2048	12.1	13.1	93.0	109.0	1.1	4.8

are categorized into private, public and grid. Each connection point provides connectivity to a different set of smart distribution grid use cases. We assume the use case specific traffic volume per connection point to increase linearly during the period under study, reflecting increasing penetration of elements such as EVs or photovoltaic units. Table 2 provides an overview of this mapping of Smart Grid use cases on different types of connection points. For example, the traffic volume of the DG/DS use case at private connection points is predicted to increase by factor three between 2018 and 2048. Compared to private connection points, public ones experience five times higher DG/DS traffic demand in 2018 already. Combining the results of Tables 1 and 2, transmission direction-specific (downlink/uplink) aggregated data rate requirements can be derived for each type of connection point. Obtained traffic demands are given in Table 3.

3.1.3 End-Consumer Mobile Traffic

Mobile broadband traffic of end-consumers is modeled, using concepts from [6], as:

$$R(t) = \frac{p}{N_{op}} \alpha(t)(r_h s_h + r_a s_a) \text{ [Mbps]} \tag{4}$$

with p and N_{op} being the number of users and telcos. The impact of busy hours is considered with the help of factor $\alpha(t) = 0.16$. We distinguish different types of users with $s_h = 20\,\%$ share of heavy and $s_a = 80\,\%$ average users. For average users a mean data rate of $r_a = 31\,\text{kbps}$ is assumed, whereas heavy users incur data rates of up to $r_a = 250\,\text{kbps}$ [6]. The traffic per end-consumer is assumed to increase by $10\,\%$ per year.

3.2 Network Dimensioning

Similar to traffic modeling, network dimensioning distinguishes infrastructures for transmission and distribution grid.

3.2.1 Transmission Grid Infrastructures

For transmission grid communications, we consider fiber optic technology, whereas cellular networks are not considered feasible due to long distances between substations. Also, wireless technologies are excluded from intra-substation communications because of potential electromagnetic interference.

Therefore, a realistic fiber infrastructure is modeled on top of a reference power grid with cables being carried along the power lines. Each substation of the power system serves as a node of the communication network, hosting optic and electric switching equipment. These junctions are designed, considering basic concepts of multilayer node models described in [43]. On the optical

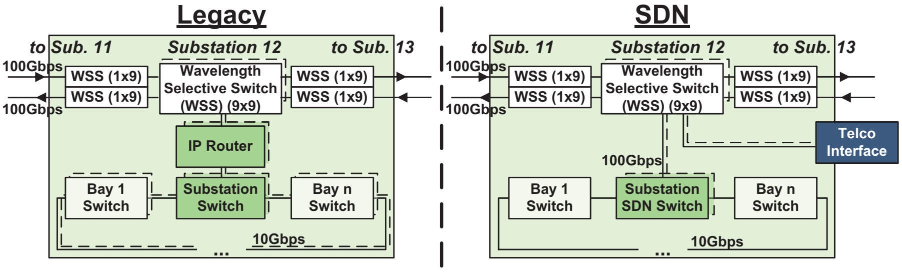

Fig. 3 Substation components for legacy and SDN fiber networks

side, we use color- and directionless Optical Cross-Connects (OXCs), employing the components shown in Figure 3. 100 Gbps wide area links exceeding 80 km integrate an in-line amplifier to increase the reach of the signal [43]. Figure 3 comprises the electrical side as well, differentiating between legacy and SDN-enabled networks. In the legacy case, Internet Protocol (IP) routers connect to the substation LAN via the substation switch. For resilience, all active components are redundant with a 10 Gbps dual-ring topology linking the bays. In contrast, the SDN switch connects directly both to the Wavelength Selective Switch (WSS) and the substation LAN. Due to enhanced fault tolerance mechanisms, redundancy is reduced on this level. Hence, single ring topologies suffice for substation LANs. In addition, one SDN controller serves 100 switches (two being the minimum per network) [37].

To respect different levels of fiber-optical infrastructure penetration in real transmission systems (e.g. 22,000 of 105,000 km of power lines equipped with fiber at French utility RTE [45, 5]), our framework covers greenfield and brownfield scenarios by allowing to scale the ratio of utilized existing infrastructure. Increasing this percentage results in diminishing CAPEX of network installation. Yet, for the SDN scenario we assume that existing active components need to be upgraded for compliance. Such upgrades may be realized by software updates or more cost-intensive hardware replacements. Since these measures have to be evaluated on a case by case basis, the hardware / software upgrade ratio can be adjusted.

3.2.2 Distribution Grid Infrastructures

Based on our evaluations in [14], we select cellular networks as most suitable access technology for distribution grid communications. While in previous work we analyzed different frequencies and penetration levels in detail, we limit this study to 4G+ at 800 MHz. The combination with SDN in the backhaul/core marks the transition to 5G [1, 33].

Radio network dimensioning considers the factors coverage and capacity. Coverage refers to the reach of the radio signal, taking into account its attenuation. We apply the well-established Okumura-Hata propagation model [20] - in combination with the COST 231 Hata extension [11] for frequencies above 1.5 GHz - to determine the maximum radius for a base station to serve end devices. Evaluation is performed for urban, suburban and rural areas, as propagation characteristics are affected by building density. On basis of the determined radii, the number $n_{bs,coverage}$ of base stations required can be calculated statistically. This approach is summarized mathematically by Equation 5,

$$n_{bs,coverage} = \frac{A}{\pi \cdot \left(10^{\left(\frac{L - L_{in/base} - 69.55 - 26.16 \cdot log(f) - c_t + 13.82 \cdot log(h_b) + c_a}{44.9 - 6.55 \cdot log(h_b)}\right)}\right)^2}, \quad (5)$$

with A being the area to be covered by the communication network. L denotes the maximum allowed path loss in dB, which may be reduced by factors $L_{in/base}$ for considering additional indoor/basement attenuation. Also, the frequency f in MHz and the heights of base stations h_b and user devices h_m (in m) significantly influence the size of the area that can be served. h_m is considered as part of the correction factors c_t and c_a, defined in [20].

This network design is complemented by capacity-based dimensioning, assessing the infrastructure's capability of handling certain amounts of communication traffic. Capacity-wise, the required number of base stations is determined by the minimum data rate per density area, divided by the maximum capacity of a single base station. In turn, this cell data rate depends on the available bandwidth B and the spectral efficiency η of the employed technology. Spectral efficiencies vary between up- and downlink. Therefore, both transmission directions are considered separately. These relations are expressed in Equation 6, providing the required number $n_{bs,capacity}$ of base stations capacity-wise,

$$n_{bs,capacity} = \max\left(\frac{n_{dev} \cdot R_{DL}}{\eta_{DL} \cdot B_{DL}}, \frac{n_{dev} \cdot R_{UL}}{\eta_{UL} \cdot B_{UL}}\right), \quad (6)$$

with n_{dev} being the total number of devices and $R_{DL/UL}$ the minimum data rate requirement per device in downlink respectively uplink direction (in Mbps). Finally, the overall number of base stations is determined as the maximum of both dimensioning approaches.

3.3 Operator Model

The operator model comprises two alternatives for ownership and operation of the communication network as well as different levels of cooperation:

1. the utility runs a dedicated infrastructure *or*
2. the telco offers communication services to the utility, using its existing ICT infrastructure.

On the transmission system level, only dedicated fiber networks of the utility are dimensioned explicitly, whereas telco involvement is modeled technology-agnostic utilizing a device-dependent service fee. We assume that the combination of dedicated, utility-owned networks and communication services provided by the telco, presupposes the application of SDN. Slicing capabilities of SDN enable hard service guarantees for critical services within a shared third-party infrastructure. Accounting for facilitated interfacing, only the combination of SDN-enabled networks is considered. Dimensioning of the cellular distribution grid infrastructure is analyzed from both parties' point of view. Hence, service fees can be derived on basis of the actual expenses of the telco.

3.4 Consideration of Software-Defined Networking Enabled Benefits

With regard to power system infrastructures, we particularly consider the impact of reduced administration effort and downtimes. Supposing gradual conversion to SDN-enabled equipment, we exclude the aspect of less costly hardware, but rather assume that - in the worst case - equipment costs may increase due to additional software development effort. The reduction of redundant hardware is considered, wherever applicable. Energy savings are included on basis of device consolidation only. Finally, network sharing is applied as enabler for major cost savings in Smart Grid communications. In contrast, additional efforts for SDN controller hardware and the development of corresponding software (in-house vs. external) raise the expenses of SDN solutions.

3.5 Communications Infrastructure Cost Modeling

Cost modeling is split into Capital Expenditures (CAPEX) and Operational Expenditures (OPEX), which are subdivided according to equipment types and tasks. While few CAPEX components are affected by SDN, there are significant deviations in several OPEX components. In addition to the typical evaluation parameters *Total Cost of Ownership (TCO)* and *Net Present Value (NPV)*, we introduce the measure of *discounted costs per device and month*, which breaks down the NPV onto an average monthly basis.

3.5.1 Capital Expenditures

Table 4 provides an overview of all CAPEX-incurring factors, which are discussed in more detail below.

Network links Expenses for fiber-optic network links and their installation are relevant for 1) the complete transmission system infrastructure and for 2) distribution grid backhaul/core connections. Cable pricing is identical at $140\,\frac{\mathrm{EUR}}{\mathrm{km}}$ [25]. In contrast, installation along power lines of the transmission grid amounts to $3{,}000\,\frac{\mathrm{EUR}}{\mathrm{km}}$, whereas underground installation in distribution infrastructures doubles this value [25].

Table 4 CAPEX components of fiber-optic transmission and cellular distribution grid infrastructure

Factor	**Network Element**	
	Transmission	*Distribution*
Network links	all connections	backhaul / core only
Network equipment	OXC, IP routers, SDN switches	base stations, core routers
Core / control units	SDN controller	EPC, SDN controller
Real estate	router, switches	base stations, router
Network planing	all	all

Network equipment The costs of network equipment comprise expenses for the optical and electrical components of each switching node and for base stations in the distribution grid. OXC component costs range from EUR 230 for the 48 port 10 Gbps short range transceiver to EUR 110,000 for the WSS (9x9) [43]. Depending on the scenario, prices of SDN switches and IP routers are between EUR 10,000 and EUR 13,000 [25]. Base stations are considered with total costs of EUR 100,000 and EUR 200,000 for rooftop respectively tower installation [3].

Core components Costs for core components include expenses for SDN controllers and the Evolved Packet Core (EPC) of cellular networks. SDN controller costs encompass hardware and software development efforts, including fundamental functions as well as security, reliability and traffic engineering measures. Standard server hardware with prices of EUR 170 per processing core [42] are employed as driver for these expenses.

Real estate This factor considers additional property purchases for housing equipment on a per square meter basis of EUR 1,500 to EUR 3,000 [10].

Network planning Upfront network planning is integrated, based on personnel costs associated with the dimensioning process. We assume that one engineer requires five hours for the planning of one site with a total of 30 sites in the first scenario (c.f. Section 4) and about 12,000 sites in the second scenario (c.f. Section 5). The total planning time is then multiplied by an hourly wage of EUR 77 [51]. These expenses are considered as part of the CAPEX as they occur only once at the beginning of the project (not repeatedly), thus resembling investment costs structurally. In literature, classification of this kind of expenses varies [54].

3.5.2 Operational Expenditures

The different OPEX components are summarized in Table 5 along with their respective shares of overall OPEX and potential SDN-enabled savings, derived from [22]. To account for uncertainty in the assumptions on these

Table 5 OPEX components and respective savings due to SDN (*NA = Not Applicable*) [22]

Factor	**Cost Share**		**SDN-enabled Savings**	
	Fiber Network (Section 4)	*Cellular Network* (Section 5)	*Best Case*	*Worst Case*
Network operation	23 %	24 %	31 %	14.5 %
Maintenance	32 %	20 %	25 %	5 %
Repair (hardware, staff)	13 %	7 %	*NA*	*NA*
Repair (traveling)			95 %	80 %
Energy costs (10 % sites)	23 %	24 %	7 %	2 %
Real estate (10 % sites)	3 %	21 %	5 %	3 %
Administration	7 %	3 %	*NA*	*NA*

savings, we distinguish between SDN best and worst case scenarios.

Network operation and maintenance These expenses stand out as major drivers of the OPEX. Both are calculated on basis of personnel costs with the number of employees being proportional to the network size. Personnel costs include supplements to social insurance, taxes, used tools and software, resulting in expenses of EUR 70k to EUR 120k per employee and year [51]. Network operation expenses are calculated, using the number of active components as key driver. It is assumed that in legacy networks each engineer manages 120 active components during his shift, whereas in the SDN best case this figure can be improved to about 160 per person. This enhancement can be achieved based on almost fully automated network monitoring and control with the human operator being present for supervision only. For example, new functions or upgrades can be deployed without human intervention. In addition, the SDN infrastructure comprises less active components. SDN's reduced administration efforts decrease operation costs by up to 31 % [22].
To calculate maintenance expenses the number of active components is applied as key cost driver as well. In this case, one employee is assumed to handle the continuous maintenance of 20 components in legacy networks. In comparison, SDN requires less knowledge on different hardware models and operating systems. Hence, maintenance expenses can be decreased by up to 25 % [22]. This corresponds to a ratio of 30 components being handled by one employee.

Repair Expenditures for repair are subdivided into costs of hardware replacement, employees and traveling. Replacement costs depend on the Mean Time Between Failures (MTBF), whereas personnel costs are a function of MTBF and Mean Time To Repair (MTTR). Equipment-specific data for these parameters are obtained from [25, 54]. For example router and switches are considered to experience 0.08 failures per year (inverse of the MTBF) and to be repaired within three hours (MTTR). Per component replacement costs are assumed to be equivalent to the original price. To obtain repair-related labor expenses, the MTTR is multiplied with hourly wages of EUR 45 and EUR 77 respectively (for different qualification levels) [51]. For this study, we assume that both, hardware replacement and labor costs, are not affected by SDN as the failure probability is not diminished. In contrast, traveling costs for field repairs are reduced by optimized scheduling of repair operations. As described in Section 2.2, this results from improved network monitoring and centralized, software-based troubleshooting.

Energy costs These expenses are a product of device-specific energy consumption, derived from [3, 12], and energy prices of $0.12\,\frac{\text{EUR}}{\text{kWh}}$ for the scenario region [53]. As we consider SDN-induced reductions on basis of device consolidation only, savings are limited to 10 % of the sites.

Real estate Similar to energy costs, savings on real estate rent are based on consolidation. Hence, we restrict these reductions to the same share of sites. Generally, real estate costs are calculated as the rent per sqm ($100\,\frac{\text{EUR}}{\text{sqm}\cdot\text{year}}$) , multiplied with the size of the sites (about 20 sqm per site).

Administration Expenses for administration are determined, based on labor expenses [51], using the number of network components as key driver as well. They include tasks such as accounting, legal services and general management.

3.6 Summary of the Proposed Modeling Approach

To recap, our modeling approach follows the sequence of steps given below:

1. First, the modeling perspective is determined. Assuming the point-of-view of a utility, a trade-off between creating own infrastructure and acquiring third-party communication services needs to be made. In contrast, from the perspective of a telco, the focus is on operating infrastructure and offering services to utilities.
2. Next, the target area is identified, including size and population. Also, estimates are made on the penetration of Smart Grid devices in relation to the population.
3. The traffic per Smart Grid device is calculated in terms of minimum data rate requirements and aggregated per communication connection point. Afterwards, the traffic demand within the entire target area is deduced.
4. Network dimensioning is performed with regard to
   (a) coverage, i.e. network availability, based on target area properties.
   (b) required capacities, defined by traffic dimensioning.
   Thus, the quantity of necessary network equipment is obtained.
5. CAPEX and OPEX for installing and operating the communication infrastructure are derived on basis of network equipment quantities and respective costs.

6. During cost analysis, savings, associated with the SDN approach, are considered.

The presentation of evaluation results focuses on the outcome of steps 5 and 6, performing various sensitivity analyses on individual parameters.

4 Economic Feasibility of Software-Defined Transmission Grid Communications

In the following, the transmission grid scenario is introduced and corresponding evaluation results are presented.

4.1 Transmission Grid Scenario Description

The scenario builds upon the IEEE 39 bus system / New England Test System (NETS), a well-established reference system for power grids. As shown in Figure 4, a corresponding communication infrastructure is modeled on top of the power system. Substations are modeled on a statistical basis with six bays each, interconnected in a ring topology. Each bay consists of four Intelligent Electronic Devices (IEDs) for protection, control, measurement collection and switching. For dimensioning substations and their bays, publicly available data of real substations [40] are analyzed. In case of an SDN-enabled infrastructure controllers are placed at substations 3, 6 and 16, which are central

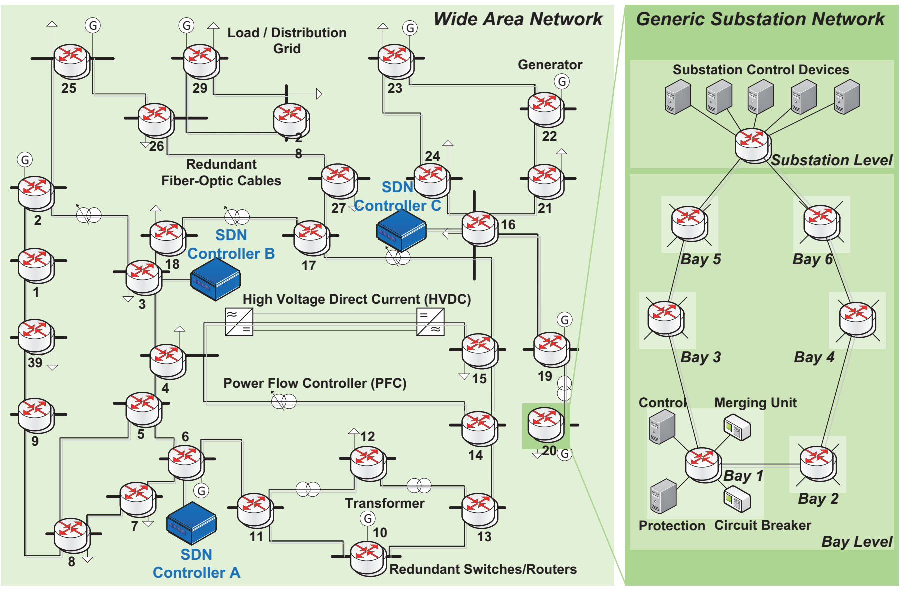

Fig. 4 Transmission grid scenario based on the New England Test System

junction points for different network parts. Further, the following parameters are utilized throughout the scenarios:

Existing infrastructure: The ratio between new and existing communication infrastructure is scaled between 0 % (greenfield scenario) and 100 % (brownfield scenario).

Network technology: Technology-wise, it is differentiated between legacy and SDN infrastructures, with the latter being subdivided into best and worst case. To consider higher prices during market entry of SDN-enabled hardware, the worst case comprises 10 % higher costs for switches. Also, the best case is based on more optimistic assumptions on the OPEX-reducing potential of SDN (c.f. Table 5). Subsequently, these cases constitute an operational range for SDN-enabled Smart Grid infrastructures.

Hardware / software upgrades: In case existing communication infrastructure is reused, components need to be adapted to support SDN. Such modifications can be realized with the help of software updates only or it might be necessary to replace both software and hardware. The ratio between these types of upgrades can be varied freely.

Operator model: Telco involvement can be scaled with respect to the ratio of existing infrastructure. It is modeled in an abstract manner, setting the monthly service fee to the same level as the utility's cost per device and month. This price marks the maximum service fee, acceptable for the utility, and maximizes the telco's profit. It bases on the assumption that the telco has full knowledge of the utility's cost structure.

Evaluation period: We consider an evaluation period of 30 years [50]. Even though such a long time interval may involve economic uncertainties and does not reflect ICT innovation cycles, it is a valid evolution period for the energy sector.

Leasing of excess capacities: Within a dedicated sensitivity analysis we consider leasing excess traffic capacities to third parties, providing financial benefits from the deployment of the network. Income from fiber lease is computed, assuming earnings of 1794 $\frac{\text{EUR}}{\text{km}}$ of connection length [37].

Overall, if not specified otherwise the following assumptions are applied:

- Existing infrastructure: 0 % (greenfield scenario)
- Hardware / software upgrades: 50 % hardware/software, 50 % software (if existing infrastructure > 0 %)
- Operator model: own utility network, no telco involvement
- Evaluation period: 30 years [50]
- Leasing of excess capacities: no

4.2 Evaluation Results

Evaluation of communication solutions for transmission power grids is subdivided into a base scenario and subsequent sensitivity analyses.

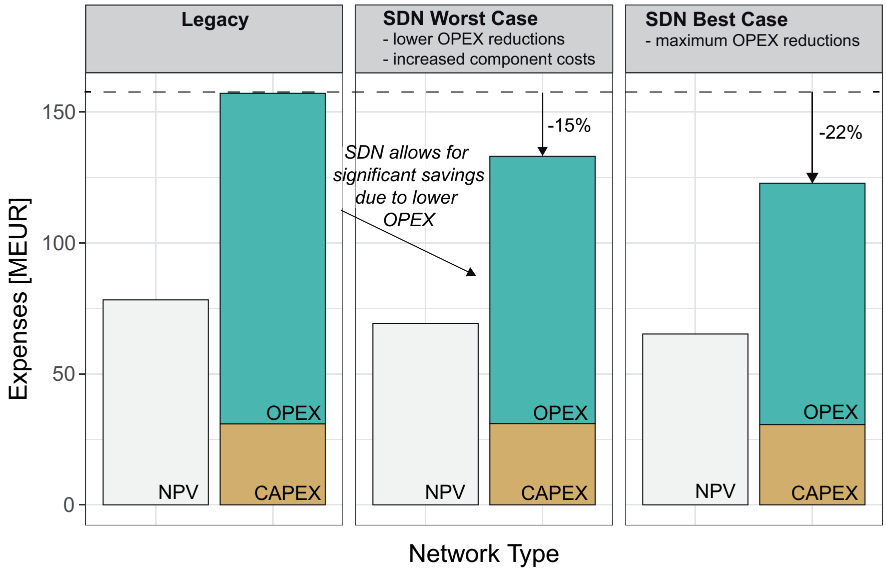

Fig. 5 Comparison of CAPEX, OPEX and NPV for legacy and SDN best/worst case networks in a greenfield approach

Base Scenario Following the modeling of transmission grid traffic (c.f. Section 3.1.1) and corresponding network dimensioning (c.f. Sections 3.2.1 and 4.1), NPV and TCO (sum of overall CAPEX and OPEX) are determined. These parameters are applied to compare different technological options for connecting substations of the transmission power grid - i.e. legacy networks and SDN infrastructures - in Figure 5. As noted above, we distinguish SDN worst and best case with varying degrees of cost reduction. During the 30 year evaluation period, the use of SDN enables a drastic OPEX decrease from EUR 126M to EUR 92M in the best, respectively EUR 102M in the worst case. As described in Section 2.2, major drivers for this development are more efficient network operation and maintenance. Meanwhile, CAPEX show only minor variations. Thus, the NPV decreases by merely 17 % in the best and 11 % in the worst case.

Sensitivity Analysis on Reusing Existing Infrastructure This sensitivity analysis, shown in Figure 6, investigates how the NPVs (y_1-axis) of the different communication solutions depend on the percentage of existing infrastructure (x-axis). Hence, more or less equipment and fiber-optical cables are already present and can be put to use for the Smart Grid communication infrastructure. Even though SDN requires software and possibly also hardware upgrades of the active networking components, in all scenarios CAPEX decrease with increasing share of existing infrastructure. It follows directly that the NPV declines proportionally as well. The two SDN cases define an operational range, within which realistic outcomes may be situated, as shown

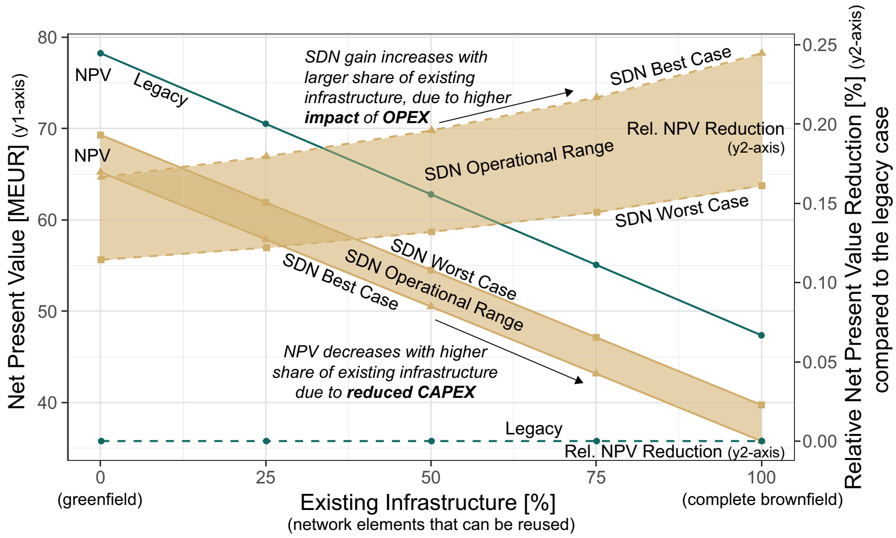

Fig. 6 NPV (y_1-axis) and SDN-based NPV reduction in relation to the legacy case (y_2-axis) for varying shares of existing infrastructure

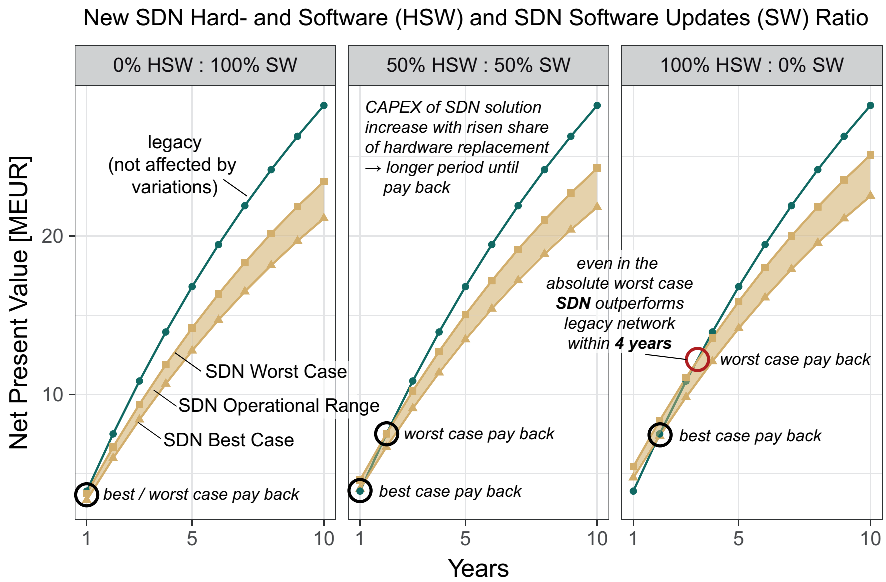

Fig. 7 NPV and pay back periods of upgrading existing infrastructure to SDN, considering different ratios of new hard- and software to software upgrades

in Figure 6. Due to the rising impact of OPEX, reductions in both SDN cases are relatively higher than in legacy networks. This phenomenon is illustrated by the dashed lines, representing relative NPV reductions compared to the legacy case (y_2-axis).

Sensitivity Analysis on SDN-Induced Upgrade Demand As mentioned previously, reusing existing network elements for SDN-enabled infrastructures requires updating the software of the respective devices or even the complete replacement of software and hardware. It has to be highlighted that optical components are not affected by such upgrades. Subsequently, presupposing the most challenging scenario of fully existing infrastructure, Figure 7 visualizes the impact of different upgrade approaches on the NPV of SDN-based solutions. We distinguish three different configurations:

- 100 % software updates (no hardware/software upgrades),
- 50-50 % shares of software updates and hardware/software upgrades,
- 100 % hardware and software replacement.

If all network adaptations are done by software, both SDN best and worst case improve upon the NPV of legacy networks within the first year. We refer to this phenomenon as *pay back* of the SDN solution. In the best case, the pay back remains unchanged for the fifty-fifty split between hard- and software updates, whereas the period increases to approximately two years in the worst case. Finally, applying 100 % new hard- and software, the pay back rises to two respectively four years.

Sensitivity Analysis on Acquiring Communication Services The previous analyses do not study different operator models such as the involvement of telcos, offering communication services to Smart Grid applications. In contrast, Figure 8 focuses explicitly on the interdependency between the NPV (y-axis) and the share of third-party involvement (x-axis) in the SDN best case scenario. The set of curves illustrates different ratios of existing infrastructure. First, it has to be noted that the share of already present network elements limits potential telco involvement. If available systems can be reused, Smart Grid devices attached to such networks will not utilize third-party services.
For percentages of existing infrastructure larger than 5 %, Figure 8 indicates decreasing NPV in case of increasing telco involvement. In contrast, for ratios smaller than this, the NPV rises with increasing involvement, since the per device effort escalates. This development is caused by the need for building a complete new infrastructure for only few devices, whereas the majority of elements is served by third party networks. In addition, the telco gains power over the utility and is able to dictate prices quite freely, in particular if its share is higher than 75 %. Overall, fluctuating progression of the curves is due to permanence, e.g. caused by the discrete development of staff sizes.

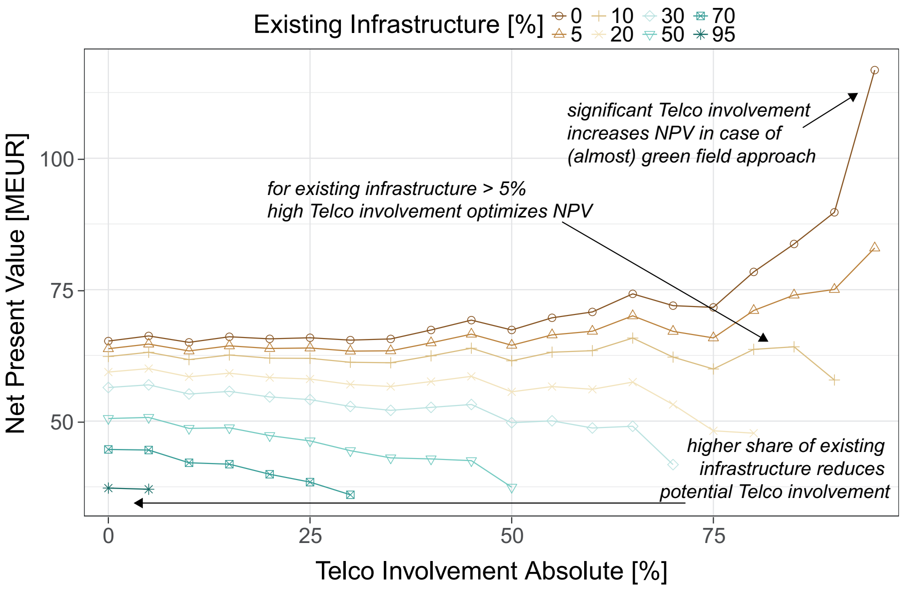

Fig. 8 Impact of interdependency between existing infrastructure and telco involvement on NPV in the SDN best case scenario

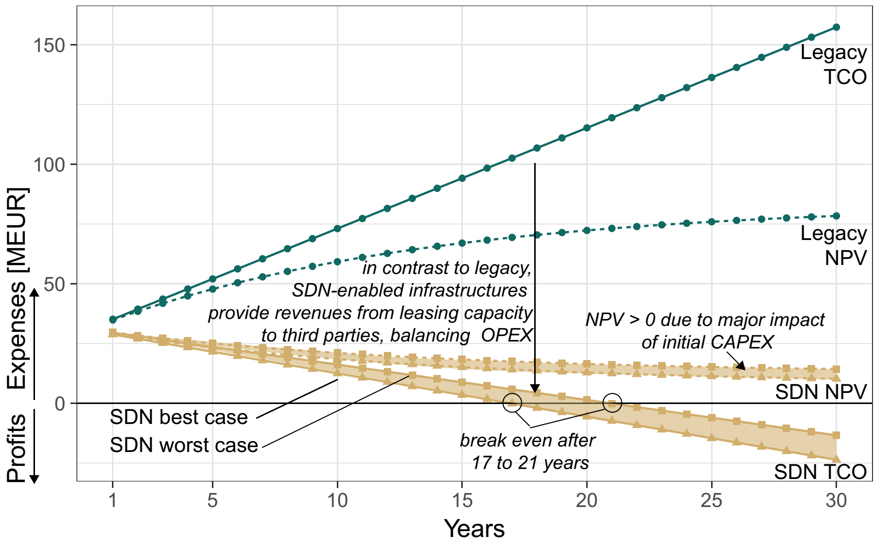

Fig. 9 Break even analysis of SDN-based fiber infrastructures, profiting from leasing fiber capacities to third parties, in comparison to legacy networks

Break-Even Analysis based on Benefits from Leasing Capacity to Third Parties Next, the utility's benefits of leasing excess capacities of their dedicated fiber-optic infrastructure to third parties are studied. Therefore, SDN-enabled network slicing is integrated into the analysis. It provides the basis for managing unused network resources, assigned to separate slices. In contrast, we do not consider income from marketing excess capacities in legacy networks, due to the inability of 1) flexible resource allocation and 2) traffic isolation, which would be a precondition for hard service guarantees. Figure 9 shows the development of TCO and NPV for the different network types over a 30 year period. With respect to the TCO, SDN-based solutions reach the break-even point within a range of 17 to 21 years (c.f. Figure 9), induced by the leasing revenues. Due to the major impact of the initial CAPEX, profits are achieved only after more than 30 years according to the NPV. Nevertheless, this analysis highlights that leasing excess network capacities helps to significantly limit or even balance the efforts of SDN-enabled infrastructures.

5 Software-Defined Shared Infrastructures

Introduced by the results of Figure 9, this section deals with shared infrastructures on basis of SDN, broadening the scope to transmission and distribution grid communications.

5.1 Holistic Smart Grid Scenario Description

The NETS transmission grid is extended by statistically modeling distribution systems and associated mobile communication networks. As the system

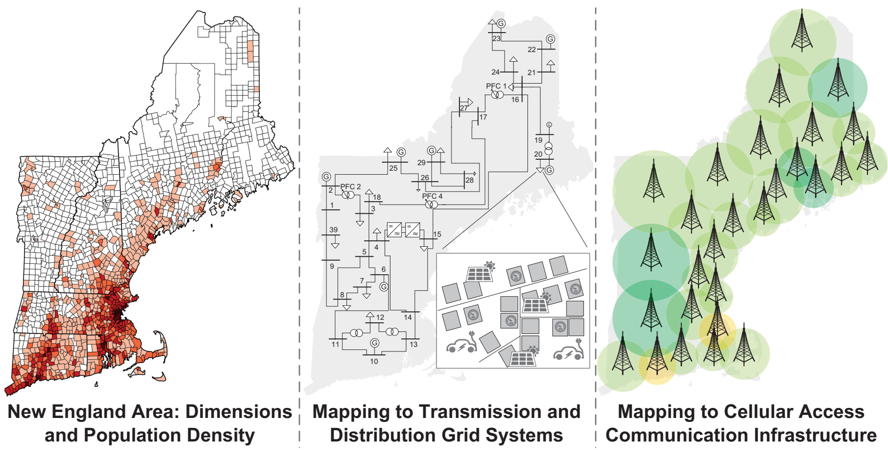

Fig. 10 Holistic transmission and distribution grid scenario, integrating actual New England dimensions and population (density) data from [49]

originates from the actual New England power grid, we dimension the ICT infrastructure for the entire area (184,570 km^2). To integrate distribution grid devices and corresponding traffic, real population count (14 million) and density data [49] are combined with the device penetration assumptions in [14]. Also, population data are used to include end-consumer traffic, as shown in Figure 10.

5.2 Evaluation Results

In the following evaluation results are presented from the perspectives of both telcos and utilities.

Telco's Perspective: Mobile Broadband Network Focusing on the telco's perspective, Figure 11 illustrates the expenses of creating a mobile access network for the New England area. Therefore, the dimensioning principles, introduced in Section 3.2.2 are applied, considering traffic capacities, discussed in Sections 3.1.2 and 3.1.3. From left to right, the TCO for different consumer portfolios are shown in Figure 11, where further use cases are added in each of the first three portfolios, as indicated by cells marked with an 'x' in the table at the top of the figure. Subsequently, the TCO increase slightly in every step. Due to mobile end consumer's need for broad coverage and high data rates, such infrastructures require only minor enhancements to suffice for distribution grid communications. However, the costs per device and month can be reduced drastically from EUR 2.67 to EUR 0.85. This is due

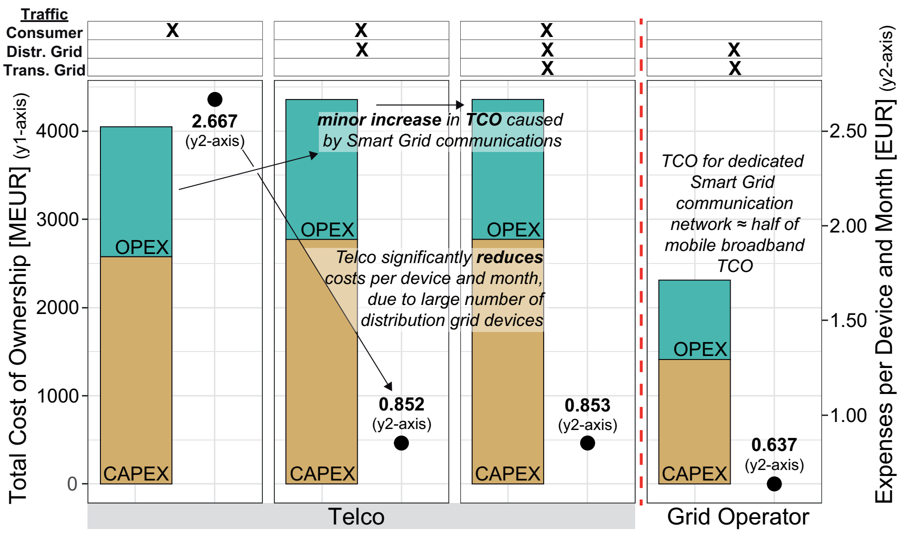

Fig. 11 Telco's perspective: expenses for mobile broadband infrastructures used for end-consumers only or in joint use with Smart Grid communications

to the fact that this scenario comprises large numbers of smart distribution grid devices, in this case up to 9.8 million connection points in 2048. The number of connection points is determined based on the assumption that every household is equipped with at least a smart metering device (in 2018: about 5.6 million [49], in 2048: about 7.9 million households [49]). Further, we consider connection points in commercial buildings (about 0.3 million [52]), industrial buildings (estimated the same quantity as commercial buildings) and businesses in mainly residential buildings (assumed to be half the total number of commercial buildings). These connection points allow reaching smart meters, distributed energy resources or DSM-enabled appliances. The population count [49] is used as reference to scale comprehensive United States (US) data down to values appropriate for the New England area. Finally, parking lots with EV charging facilities are included. Relating estimates on parking spaces throughout the US [27] to the New England area, results in about 21 million spaces for this scenario. Accounting for different types of parking lots, we assume that on average 20 spaces share the same wide area communication access, yielding approximately 1.05 million connection points.
Subsequently, the slightly risen TCO (or NPV) are divided among a much higher number of customers/devices, thus leading to the described reduction of costs per device and month. Hence, integrating a network slice for Smart Grid traffic is highly cost-efficient for the telco as even low service fees would easily generate considerable profits. In comparison, the forth field of Figure 11 shows the expenses for a dedicated distribution and transmission cellular infrastructure from the utility's point-of-view. The TCO for such a network amounts to EUR 2.3B, which is about half the expenditures of the telco's shared infrastructure.

Utility's Perspective: Make or Buy Decision Figure 12 contrasts the utility's above described costs (c.f. Figure 11 last column) with different levels of telco involvement. It ranges from telco services for distribution grid traffic only to a comprehensive service offer, which excludes only intra-substation communication (c.f. table at the top of Figure 12).
As service fees we assume EUR 3.00 and EUR 10.00 per month for distribution and transmission grid devices respectively. These prices exceed significantly the telco's costs shown in Figure 11 and consider different service requirements. Figure 12 highlights that the costs for a comprehensive, utility-owned infrastructure (first column) are well-above those of solutions, which include telco services. In these cases, service fees for distribution grid communications dominate the TCO, which is due to the large number of devices. Minimal expenses are achieved if a network slice for both transmission and distribution system traffic is acquired from the telco (last column). However, combining communication services for smart distribution grid applications with a dedicated, SDN-based infrastructure for the transmission grid (center column), allows for optimal costs per device and month. Nevertheless, cost deviations are minimal. In the latter case (center column in Figure 12), revenues from

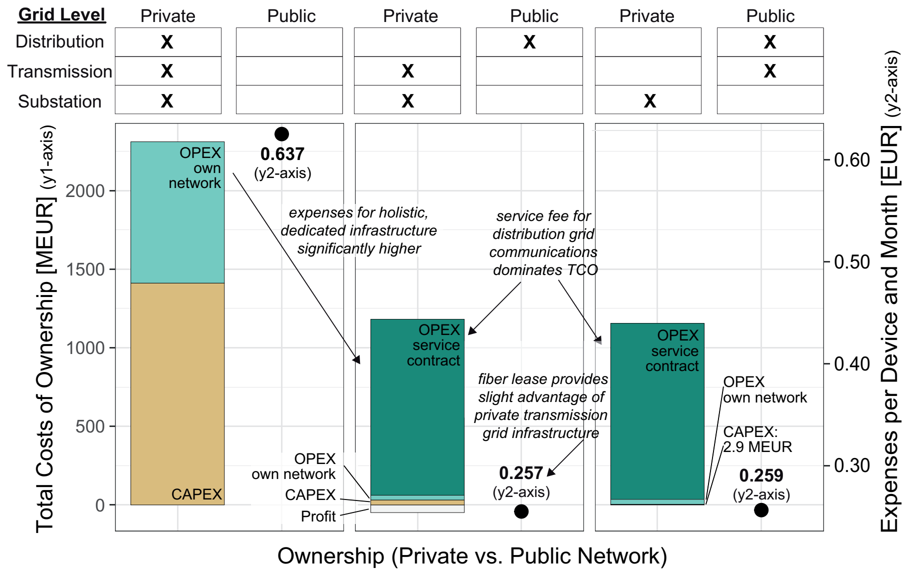

Fig. 12 Utility's perspective: expenses for different combinations of dedicated, private infrastructures (*make*) and purchased communication services over public networks (*buy*)

leasing fiber capacity to third parties balance the additional expenses of the fiber-optical infrastructure.

6 Conclusion and Outlook

In this paper, we analyzed the techno-economic implications of applying SDN for power system communications. Economic advantages were identified to be strongly OPEX-driven. To obtain numerical proof of these benefits, a holistic approach was created, consisting of traffic, network, operator and cost modeling. Analysis was split into two scenarios, evolving from the well-establish reference power grid NETS.

1) In the first step, we focused on the transmission grid and compared SDN and legacy fiber-optical infrastructures. The SDN solution was shown to improve significantly the economic efficiency. Even in case of 100 % existing communication infrastructures, OPEX savings allow SDN to outperform legacy networks within a maximum of 4 years. Further, SDN-based network slicing enables the lease of excess capacity to third parties, generating additional revenue. Thus, the break-even for the greenfield installation of a dedicated fiber-optical infrastructure is achieved after 21 years in a worst case scenario (17 years in the best case).

2) In the second step, the scenario was extended to include the distribution grid. Therefore, we modeled wireless broadband infrastructures in combination with SDN-based backhaul / core, as suggested for 5G. Network slicing is

applied to achieve hard service guarantees for critical Smart Grid services. It was highlighted that setting up dedicated cellular networks for Cyber-Physical Systems (CPSs) is not competitive, whereas shared infrastructures with mobile broadband end-consumers provide economic benefits for both telcos and utilities. From a utility's point-of-view, the combination of dedicated SDN-enabled infrastructures for transmission grids with third-party distribution grid communication services is proven to be nearly equivalent to holistic service contracts for power system communications.

Though beyond the scope of this article, our modeling approach may be easily applied to other energy systems such as gas, by utilizing appropriate traffic patterns and numbers of devices. Furthermore, we aim to add emerging 5G radio access technologies to the evaluation.

Acknowledgement

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