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A Day Late and a Dollar Short: Intertemporal Revenue Cap Regulation Considering Stranded Assets

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Abstract

The European Union's goal of carbon neutrality by 2050 requires a major reduction in natural gas use for residential heating. However, gas grid equipment, amortized over 45 years in most countries, risks becoming stranded assets. The literature suggests that regulatory shocks could justify enhanced cost recovery during the remaining grid use period to reduce social costs of asset stranding. Under revenue cap regulation, increased cost recovery and higher tariffs may prompt households to switch to alternative technologies. These premature defections risk undermining cost recovery and place additional financial burdens on remaining households. Regulators face a trade-off between efficient defections and cost recovery. This paper introduces an intertemporal equilibrium model to explore network tariffs and household responses under different revenue caps and analyze their welfare implications. We demonstrate that degressive front-loading is an optimal strategy, balancing cost recovery with household exits, reducing stranded assets, and minimizing social costs. Furthermore, we find that, under the predominant revenue cap schemes, total cost recovery is often not achieved. We also examine distributional implications, showing how tariffs burden heterogeneous households. This research offers insights for policymakers and regulators into mitigating stranded costs while managing household defection impacts in countries with revenue cap regulation and young gas grids.

Keywords: Gas, regulation, revenue caps, network tariffs, household response

JEL classification: D15, D42, D63, L12, L38, L42, L51, L95

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1 Introduction

The energy sector's transition away from fossil fuels, such as natural gas, is pivotal for achieving political decarbonization goals (Directorate-General for Climate Action, 2024a). In 2022, natural gas accounted for 30.9% of final energy consumption in households in the European Union (EU) (Eurostat, 2024). In 2023, the German gas distribution grid supplied 20 million households and 1.8 million enterprises, primarily for heat generation (Westnetz, 2024).

Various drivers are causing a declining demand for gas, including the rising attractiveness of low-carbon alternatives like heat pumps and district heating solutions, emphasized by factors such as cost reductions in alternative heating technologies and uncertainties in gas prices and supply. Moreover, the EU Emissions Trading System II (ETS II) will introduce a carbon price on emissions from fuel combustion in buildings [1], while at the same time providing financial support for retrofits and the installation of heat pumps via the Social Climate Fund (Directorate-General for Climate Action, 2024b). Acknowledging the coherent declining paths across energy system studies published by European Commission (2024); IEA (2023) for European countries, and BCG and Prognos (2018); Deutsche Energie-Agentur GmbH (dena) (2021); Prognos, Öko-Institut, Wuppertal-Institut (2021); Sensfuß et al. (2021); Öko-Institut e.V. and Fraunhofer ISI (2015) for Germany, the single biggest economy in Europe, in particular, gas distribution grids in Europe can be considered a *network in decline* according to the definition by Decker (2016). Accordingly, the gas distribution grids are expected to face a "sustained, non-temporary reduction in demand, resulting" in an under-utilization of the grid (Decker, 2016, p. 345).

The economic lifetime of the distribution grid is over 45 years in several European countries, and in some even up to 90 years (CEER, 2024). Noting that, in Germany, the average distribution grid is 29 years old (Lange, Schwigon, & Steiner, 2021, p. 72), and acknowledging the anticipated decline in demand until 2045[2], a significant part of the gas distribution grid will not be depreciated and, hence, refinanced by 2045 (Oberle, 2023).[3] In other words, there is a mismatch between the originally intended end-of-use time when the investments were made and the newly expected end-of-use time following changes in demand and political decisions (Agora Energiewende, 2023; Oberle, 2023). This development challenges the recovery of investments made into the grid in the recent past and thus might risk assets becoming stranded

[1] Carbon emissions from electricity generation is covered and priced in the existing EU ETS I.
[2] Germany has an earlier decarbonization target than the EU.
[3] There is an emerging debate on the possibilities to re-purpose the existing distribution grid. Yet, their realization as of this moment is unclear. Therefore, the present paper considers the heat pump as the main available and mature alternative for residential heating.

(Giehl et al., 2021; Wachsmuth et al., 2019).[4] Accordingly, one question is how to price natural gas for heating to address this challenge.

In economic theory, marginal cost pricing is associated with welfare-optimal decision-making and hence considered first-best. However, Boiteux (1956) identified that marginal costs are often lower than average costs, especially for capital-intensive infrastructure such as gas pipelines. Pricing solely at marginal cost would not recover these fixed costs, leading to financial losses. According to Boiteux, capital-intensive industries must charge tariffs above the marginal price for the infrastructure to be provided. Economic theory suggests that fixed costs are best recovered via a fixed tariff (Borenstein, 2016, p. 5). The fixed charge does not distort the marginal efficiency of consumption decisions because it does not alter the marginal cost price, i.e., the variable component in a two-part tariff. Households continue to make consumption choices based on the variable tariff, which aligns with the marginal cost. However, in reality, operators recover substantial shares of their fixed cost via volumetric tariffs (Costello & Hemphill, 2014; Davis & Hausman, 2021). Thereby, household decisions are distorted. Considering natural gas grids a natural monopoly, most countries either regulate the revenue of grid operators or the prices these are allowed to set.

In several European countries[5], grid operators are revenue cap-regulated. Hence, they cannot freely set network tariffs. Still, the operators are exposed to regulatory risk (new end-of-use time) that may materialize due to political decisions. The current revenue cap regulations do not yet adjust for the mismatch of intended and new end-of-use time, which would allow operators to increase tariffs to produce additional cost recovery to compensate for the reduced recovery time. Even though recovery of cost induced by stranded assets is not generally needed for economic efficiency, the literature provides reasons why the recovery of fixed costs is admissible. Simshauser (2017, p. 386) elaborates the arguments for and against cost recovery. These include, among others, moral hazard, investor expectations, efficiency and fairness & equity for operators in a natural monopoly industry, like the one analyzed in this paper.[6] He further reveals different potential social costs associated with asset stranding, such as increasing the cost of capital for future investments due to the precedence of regulatory risk. Considering all the literature he reviews, he concludes that "when reform shocks constitute large, policy-driven

[4] "Assets are considered stranded when they were prudently acquired but have lost economic value as a direct result of an unforeseeable regulatory or legislative change specific to the industry in question" (Crew & Kleindorfer, 1999, p. 64).

[5] i.e., Germany, Austria, Croatia, Czech Republic, Denmark, Finland, France, Greece, Ireland, Latvia, Lithuania, Luxembourg, Romania, Slovenia, Sweden, North Macedonia.

[6] Simshauser emphasizes that "regulators frequently force utilities to make suboptimal investments to meet universal service obligations, policy objectives or mandated environmental schemes that deviate from minimum cost. Such commitments were undertaken because returns were guaranteed".

events that breach longstanding expectations and produce an especially uneven distribution and intensity of losses, [...] recovery is appropriate".

Under revenue cap regulation, as implemented in 16 European countries, a regulatory authority allows operator-specific revenue for a defined period based on a predetermined calculation of the asset base and cost, time frame for depreciation primarily dependent on the asset type, and rate of return on capital. The operator then translates this revenue into a grid tariff charged to households. Moreover, a potential increase in tariff due to the need for accelerated cost recovery incentivizes households to switch to alternative technologies early, which again might risk desired cost recovery and burden remaining households with increasing tariffs.[7] Accordingly, in setting the revenue cap, the regulator is challenged to balance the principles of efficiency within the network (household decision) and "fairness" (operator cost recovery) over multiple periods.

The existing literature has acknowledged the cost recovery problem. Still, it is silent on the role of the revenue cap chosen by the regulator and the demand response of households induced by the corresponding tariff, especially given the *shock* of the reduced effective recovery period. Hence, it offers little insight into this dynamically reinforcing relationship and its implications for welfare in a declining network. Giehl et al. (2021); MVV Energie AG (2023); Oberle (2023); Wachsmuth et al. (2019) acknowledge tariffs will increase under current regulations in Germany and Rosenow, Lowes, and Kemfert (2024) show the same trends for several European countries, but do so not considering households as active decision-makers. Hiebert (1997) builds on the model established by Boiteux and introduces the *non-core* household that is given an investment opportunity to switch technology compared to a *core* household that cannot switch. He finds that the optimal price for the former is lower than the price for the latter. Most recently, Schittekatte and Meeus (2020, p. 120) highlight that "the more consumers can react to price signals, the more important it becomes to get the network tariffs to design right". The authors implement a bi-level model "which closes the loop between network tariff design, [to analyze] incentives for *active*, self-interest pursuing consumers, and the aggregate effect of consumer actions on the total network costs which need to be recovered by the network charges".[8] Their numerical analysis shows that an active household's reaction depends on the tariff design imposed by the grid operator.

[7]Note that, even though fixed tariffs might not distort short-term consumption decisions, they might still distort long-term investment decisions.

[8]Earlier, Hiebert (1997) distinguishes the "core" and "non-core" consumers, of which the latter is considered to have access to investment opportunities for alternative technologies in contrast to core consumers who only have access to the incumbent technology. In the presented paper, the incumbent technology is gas for residential heating with potential alternatives such as electricity (i.e., heat pump) and district heating solutions

While the contributions by Schittekatte and Meeus and Hiebert provide valuable insights, we identify three main gaps in the literature. Firstly, while the decline in gas consumption for space heating is recognized, to the best of the author's knowledge, a theoretical analysis of the welfare implications and consequences for cost recovery in a regulated network in decline that allows all households to exit the network at a certain point does not exist. The passive and core household types considered in Schittekatte and Meeus and Hiebert are assumed to remain connected to the network.

Secondly, existing contributions offer limited insight into the impact of recently arising time constraints for cost recovery. The numerical analysis provided by Schittekatte and Meeus is limited to one period. While the theoretical study of Hiebert considers two periods, one in which the non-core households can decide to invest and the period after when they have reduced their consumption due to self-generation or defected entirely, Hiebert assumes that prices charged are the same each period but differ between the two household types. Given that under revenue cap regulation, tariffs can change throughout time and are expected to increase significantly, the two-period model presented by Hiebert offers little insight into the intertemporal dynamics of tariff changes and household responses that are at the core of the investigation conducted in this paper.

Thirdly, the implications of revenue cap regulation remain under-explored. In particular, the critical role of the regulator's balancing act in setting revenue caps accounting for *active* households and the cost of non-recovery has received little attention. The existing literature assumes full cost recovery to be realized via the prices or tariffs they set. Moreover, the distributional effects of various revenue caps and corresponding tariffs across heterogeneous household types have yet to be thoroughly investigated.

This paper aims to fill these gaps by investigating the interplay between different revenue caps, their corresponding network tariffs, and the household exit behavior these induce over multiple periods, allowing all households to defect. Thereby, we endogenize the decline of demand for natural gas and disentangle the effects on household and their decisions efficiency and cost recovery of operators. Moreover, we explore the welfare implications of different regulatory objectives in setting the revenue cap that is translated to tariffs and thus corresponds to household defection. Therefore, we can assess the degree of cost recovery realized as well as the distributional implications. Accordingly, this study presents a novel approach to understanding the welfare implications of declining gas demand. To contribute to this currently understudied field, the present paper asks: *What are the welfare implications of different revenue caps in a regulated network in decline?*

We begin by employing an equilibrium model to analyze the profit maximization of network operators, who set tariffs per the revenue caps established by the regulator and the households, minimizing costs through potential fuel switching. The decision variables—the network tariff and household defection, respectively—factor into both problems, thus connecting them. The equilibrium paths from solving this interconnected program are then used to calculate welfare given any revenue cap. This allows us to establish a welfare-maximizing revenue cap that we use as a baseline to compare different regulatory objectives and their implications for welfare. Moreover, it allows us to evaluate a stylized version of the current revenue cap regulation practiced in several European countries and elucidate the challenges regarding cost recovery and the efficiency of household defection.

The results suggest degressive front-loading is an optimal strategy to balance cost recovery and household defection under time-constrained revenue cap regulation with high fixed costs (see Figure 1). Furthermore, a tariff trajectory that allows for a higher degree of front-loading minimizes the welfare loss for any assumed social value of cost recovery (see Figure 3). Finally, we show that under current revenue cap regulation, only partial cost recovery is generally possible (see Figure 5).

Consequently, this study's contribution is threefold. Firstly, this study contributes the first theoretical identification of front-loading as an optimal strategy for the regulator to balance cost recovery and household heating costs for multiple periods. Secondly, we explicitly model the *active* household in the specific circumstances of a network in decline, i.e. the gas grid that is time-constrained for cost recovery compared to the electricity grid that has been the dominant subject of investigation in the literature. Thirdly, assuming heterogeneous active households allows us to contribute insights into the distributional aspects of different revenue caps. Accordingly, the novel approach allows a more nuanced understanding of the three interconnected decisions' welfare implications and cost recovery over multiple periods. While the regulators' choice to balance fairness and efficiency is ultimately a normative choice, the conceptualization and discussions provided in this paper can help inform regulators, policymakers, and operators across Europe that currently practice revenue cap regulation.

This article is structured as follows. Section 2 introduces the mathematical model describing the interaction of tariffs and defection. Section 3 expands the model, introducing the regulator's problem and its optimal solution. In section 4, we use a numerical case study to compare the results to the regulatory status quo in respect to cost recovery, welfare and distribution implications. Section 5 concludes the paper with remarks and avenues for future research.

2 Equilibrium of Network Tariffs and Defection

The formal structure of the model comprises three interconnected levels: (1) the cost minimization of households for their heating requirements, and (2) the profit maximization of the network operator, that is, the tariff design problem, and (3) the regulator's revenue cap decision. Regarding the latter, we explore different revenue caps throughout this work to elucidate the interplay of a revenue cap, network tariffs, and defection decisions. In the model, the parameters are in uppercase letters, and the variables are in lowercase letters. The subscripts indicate time, and the superscripts denote regulatory settings. Table 1 provides a comprehensive list of all parameters and variables of the analytical analysis.

Parameter	Description
$\boldsymbol{\theta} = (\theta_Q, \theta_I) \sim F(\boldsymbol{\theta})$	Household types, here, $\theta_Q \sim \mathcal{U}(0,1)$, $\theta_I \mid \theta_Q \sim \mathcal{U}(0, \theta_Q)$. These distributions, while simple, capture two important characteristics of households. First, they allow for heterogeneity in both investment cost and heat consumption. Second, they account for the fact that investment cost and heat consumption are typically positively correlated, i.e., households with higher heat demand will generally face a higher investment to replace their heating system.
$Q(\boldsymbol{\theta}) = 2\theta_Q Q$	Heat demand of household type $\boldsymbol{\theta}$. Assumed to be inelastic with $Q > 0$.
$I_{d,t}(\boldsymbol{\theta}) = 2\theta_I I_{d,t}$	One-time investment cost of defection from gas in period t for type $\boldsymbol{\theta}$.
$\alpha(\boldsymbol{\theta}) = \frac{\theta_I}{\theta_Q}$	Relative investment cost of household type $\boldsymbol{\theta}$. For $\boldsymbol{\theta} = (0, \cdot)$, $\alpha((0, \cdot)) = 1$.
κ	Capital stock of the gas grid, i.e., accumulated investments made in the past.
$\Delta\kappa^{\mathcal{T}} = \frac{\kappa}{\mathcal{T}}$	Linear commercial depreciation of the capital stock over a period $\mathcal{T}$. If the capital should be fully depreciated until excl. T, then $\mathcal{T} = T-1$.
$P_{g,t}$	Price of natural gas, incl. taxes but without the grid tariff.
$P_{e,t}$	Price of heating electricity, incl. taxes and levies; i.e., the actual price of electricity divided by the seasonal energy efficiency ratio.
$P_{\Delta,t} = P_{g,t} - P_{e,t}$	Price difference between gas and electricity per unit of heat. We assume that $P_{\Delta,t} - P_{\Delta,t-1} \geq 0$, i.e., the relative cost of gas is non-decreasing. This may be due to environmental policy such as increasing carbon taxation.
$\tilde{\mathrm{RC}}_t$	Revenue cap designated by the regulator to the regulated monopoly.
η	Learning rate of the alternative technology.
δ	Discount factor indicating time preferences.
λ	Social value of cost recovery.
Variable	**Description**
τ_t	The network tariff, which is charged on the volume consumed.
$\tilde{\alpha}_t$	hurdle rate that characterizes the set of indifferent households and thereby identifies the share of households defected to alternative by time t. Accordingly, $(1 - \tilde{\alpha}_t)$ denotes the share of households that consume the incumbent technology in the respective period.

Table 1: List of Parameters and Variables

We will use these parameters and variables throughout the mathematical analysis. For now, we focus on the interaction of the operators' tariff decisions and households' defection decisions. The regulator's revenue cap decision will be elaborated on in greater detail in Section 3. We do not model the physical dismantling of the grid.

2.1 Agents' decision-making problems

Our model considers three distinct agents or agent groups: the household sector, the network operator, and the regulator. The households react to tariffs set by the network operator. The network operator sets tariffs based on a revenue cap, which the regulator determines. We build the model upwards from the lowest level of decision-making. First, we introduce the household sector's response to a network tariff, τ_t. After that, we analyze the network operator's problem. A Stackelberg-like structure emerges from the strategic interaction between the operator's tariff and the households' best responses. To establish the equilibrium defection and tariff decisions, for now, the revenue cap will be considered as given by the operator and households. We will relax this assumption when we elaborate on the regulator's decision space in Section 3.

2.1.1 Households cost minimization

Households minimize their total heating cost by choosing an optimal defection. The network operators' optimization problem is linked to the households' optimization problem via the network tariff. We consider households to be heterogeneous, denoted by types $\boldsymbol{\theta} = (\theta_Q, \theta_I)$. The type characteristics θ_Q and θ_I determine the per-period heat demand $Q(\boldsymbol{\theta}) = 2\theta_Q Q$ and the one-time investment cost to defect from the gas grid at time t, $I_{d,t}(\boldsymbol{\theta}) = 2\theta_I I_{d,t}$, respectively. First, for the sake of simplicity, we assume that households' heat demand is inelastic yet heterogeneous across households and time.[9] Regarding investment cost associated with defection, the IEA (2022, p.63ff) elaborates on several reasons why investment costs for heat pumps differ between households within and between countries. In addition to the upfront cost of the technology itself, they explain that costly retrofits add to the bill for households changing their heating technology (IEA, 2022, p.73), especially in the existing building stock compared to new construction. Accordingly, households differ in terms of the cost of investment.

The individual households' choice to defect is guided by comparing the benefit of waiting to invest to the cost of staying. For now, we assume that households conduct this comparison myopically, i.e., only consider the immediate cost-benefit analysis.[10]

The **benefit of waiting** is defined as the change in defection cost over time. The defection

[9] Heating requirements to establish a preferred room temperature translate into heat demand. Households' preferences for a specific room temperature usually do not vary, and public institutions such as the WHO publish guidelines for every type of room and its optimal temperature throughout the year.

[10] See (Busse, Knittel, & Zettelmeyer, 2013; Harjunen & Liski, 2014; Sallee, West, & Fan, 2016) for examples of myopia in household decisions and examples of studies identifying households are undervaluing future cost in investment decisions (Allcott & Wozny, 2014; Gillingham, Houde, & van Benthem, 2021). Moreover, a field experiment conducted by Eßer, Flörchinger, Frondel, Hiemann, and Sommer (2024, p. 22) suggests that German households are largely unaware of the future cost savings realized by the purchase of a heat pump.

costs $I_{d,t}(\boldsymbol{\theta})$ are incurred once for household type $\boldsymbol{\theta}$ that switches in t, where $I_{d,t}$ decays with a learning parameter $0 < \eta \leq 1$, i.e., $I_{d,t} = \eta^t I_d$. The learning may represent technological progress in the alternative technology but also improved processes regarding installation. Households' time preference is indicated by $\delta < 1$. For type $\boldsymbol{\theta}$, the benefit of waiting an additional period is given by $\Delta I_{d,t}(\boldsymbol{\theta}) = I_d(\boldsymbol{\theta})(\eta^t - \delta\eta^{t+1}) = 2\theta_I I_d(\eta^t - \delta\eta^{t+1}) > 0$, as $\delta < 1$. In other words, $\Delta I_{d,t}(\boldsymbol{\theta})$ is the investment cost savings of type $\boldsymbol{\theta}$ realized for waiting an additional period to defect. Note that $\Delta I_{d,t} - \Delta I_{d,t-1} \leq 0$. All else equal, lower investment cost types θ_I benefit earlier from defection: as they have lower investment costs to realize potential savings using the alternative technology, they have an incentive to leave the incumbent network first. For households where the excess cost of using the incumbent energy carrier exceeds the value of waiting, defection is optimal.

The **cost of staying** is derived through the comparison of the *running cost* per unit of heat of the incumbent technology, $P_{g,t} + \tau_t$, i.e. the gas retail price and the network tariff, and the *running cost* per unit of heat of the alternative, $P_{e,t}$, the end-user electricity costs, given a specific household type's consumption, $Q(\boldsymbol{\theta})$.[11] This gives us $P_{\Delta,t} = P_{g,t} - P_{e,t}$ as price difference between gas and electricity per unit of heat. Thus, the excess cost of consuming gas for heating is $Q(\boldsymbol{\theta})(P_{\Delta,t} + \tau_t) = 2\theta_Q Q(P_{\Delta,t} + \tau_t)$.

In any period, there are households for which the benefit of waiting for an additional period of time before investing and the excess cost of running the incumbent energy carrier are equal, i.e., $2\tilde{\theta}_{t,I}\Delta I_{d,t} \stackrel{!}{=} 2\tilde{\theta}_{t,Q} Q(P_{\Delta,t} + \tau_t) \iff \frac{\tilde{\theta}_{t,I}}{\tilde{\theta}_{t,Q}} \stackrel{!}{=} \frac{Q(P_{\Delta,t}+\tau_t)}{\Delta I_{d,t}}$. We call these indifferent types $\tilde{\boldsymbol{\theta}}_t(\tau_t)$. For brevity, we generally drop the dependence on τ_t.

We write $\alpha(\boldsymbol{\theta}) = \frac{\theta_I}{\theta_Q}$. Note that, here, $\alpha(\boldsymbol{\theta}) \sim \mathcal{U}(0, 1)$ and that $\alpha(\boldsymbol{\theta})$ and θ_Q are independently distributed. Consequently, $\alpha(\boldsymbol{\theta})$ can be understood as a household's relative investment cost compared to its consumption. Given that households with low relative investment cost defect first, α can also be understood as an ordering under which households defect. We denote by $\tilde{\alpha}_t = \alpha(\tilde{\boldsymbol{\theta}}_t)$ the relative investment cost of the frontier of indifferent households (in $\boldsymbol{\theta}$-space) at time t, where all households with $\alpha(\boldsymbol{\theta}) \leq \tilde{\alpha}_t$ have switched at t. As such $\tilde{\alpha}_t$ can be understood as a hurdle rate that characterizes the set of indifferent households and thereby identifies the share of households defected to alternative by time t as we define in Definition 1.

Definition 1. *Assume that the hurdle rate,* $\tilde{\alpha}_t = \frac{Q(P_{\Delta,t}+\tau_t)}{\Delta I_{d,t}}$, *is non-decreasing, i.e.,* $\tilde{\alpha}_t \geq \tilde{\alpha}_{t-1}$ *and not greater than* 1, *i.e.,* $\tilde{\alpha}_t \leq 1$ $\forall t$. *Then, it constitutes a defection trajectory of the*

[11] Current numbers for Germany show that an efficient heat pump is cheaper than a gas boiler, generating the same amount of heat (Eßer et al., 2024). Moreover, carbon pricing, such as the EU ETS II, will apply to gas boilers but not to heat pumps.

household sector. We write $\Delta\tilde{\alpha}_t = \tilde{\alpha}_t - \tilde{\alpha}_{t-1} \geq 0$. Further, we assume $\alpha_T = 1$, i.e., complete defection at the end of the considered horizon.

We will revisit the tariff designs under which Definition 1 yields a sensible defection trajectory. At T, we assume all consumers have defected to an alternative technology. The defection decision itself is endogenous and emerges conditional on the tariff and parameters laid out above. This myopic defection path is equivalent to a central planner optimizing the household sector under perfect foresight, as discussed in A.7.

2.1.2 Network operators' profit maximization

The network operators set network tariffs to maximize profits, potentially given a revenue cap. In reality, tariffs might have multiple components: a variable, a fixed, and additional components for taxes and levies. According to economic theory on efficient pricing, fixed network tariffs are preferable because they do not distort market price signals that guide efficient household behavior (Pérez-Arriaga & Smeers, 2003).[12] In reality, utilities often charge a fixed tariff and a variable tariff scaled by consumption, whereby the latter is often larger than the actual variable cost, compensating for the fixed charge that is smaller than it would have to be. It is suggested that cost-reflective fixed charges deter households from entering into the contract (Brennan, 2023). We leave the issue of optimal tariff components aside.[13] Since we assume inelastic (short-term) demand for heat, there is no difference to households whether a fixed, a volumetric, or a combination of the two as a multipart tariff is charged. In our setting, only the sum of the bill charged to households is relevant to their defection. Therefore, for the sake of a less convoluted exposition and closer resemblance to volumetric tariffs in practice, within our model, the tariff τ_t introduced in the household cost minimization problem above can be understood as a single volumetric tariff charged by the operator.

Given the household's reaction to network tariffs, the network operator maximizes revenue by setting the network tariff in consideration of the demand for natural gas scaled by the share of households consuming it. Hence, the upper-level problem in its most general form is given

[12] On the contrary, volumetric tariffs that are charged in addition to the price that reflects only the variable cost of delivering each additional unit increase the per-unit price for households. Therefore, if household demand reacts to prices, introducing a volumetric tariff for fixed cost recovery induces a deadweight loss.

[13] For elaborations on the debate and the implications of active households for welfare and cost recovery, the reader is pointed to Schittekatte and Meeus (2020) who investigate different tariff designs

by

$$\max_{\tau_t} \Pi = \sum_{t}^{T-1} R_t = \sum_{t}^{T-1} \delta^t \tau_t Q \; 2 \underbrace{\mathbb{E}[\theta_Q | \alpha(\boldsymbol{\theta}) > \tilde{\alpha}_t]}_{=\mathbb{E}[\theta_Q]=\frac{1}{2}} \underbrace{\Pr(\alpha(\boldsymbol{\theta}) > \tilde{\alpha}_t)}_{=1-\tilde{\alpha}_t}$$
$$= \sum_{t}^{T-1} \delta^t \tau_t Q (1 - \tilde{\alpha}_t).$$

Considering the network operators' revenue is regulated, the operator maximizes this revenue such that it does not exceed the revenue cap set by the regulator for each period:

$$Q\tau_t(1 - \tilde{\alpha}_t) \leq \tilde{\text{RC}}_t$$

Additionally, the network operator has to anticipate household sector response, $\tilde{\alpha}_t$. With that, the overall network tariff design problem is

$$\max_{\tau_t} \Pi = \sum_{t}^{T-1} R_t = \sum_{t}^{T-1} \delta^t Q \tau_t (1 - \tilde{\alpha}_t)$$
$$\text{s.t.} \quad Q\tau_t(1 - \tilde{\alpha}_t) \leq \tilde{\text{RC}}_t$$
$$\tilde{\alpha}_t = \frac{Q\left(P_{\Delta,t} + \tau_t\right)}{\Delta I_{d,t}}.$$

Due to households' ability to defect, the network operator could be unregulated but still have limited market power in increasing the tariffs. The operator effectively competes with the outside option presented by alternative technology that the household could invest into. As such they face a *natural limit* to the tariff they can set.[14]

For now, we assume that the revenue cap is exogenous to the operator's and household decision problems as it is given by the regulator. Later, we will turn to the regulator's problem, weighing welfare losses due to premature defection against cost recovery.

2.2 Solving the network equilibrium for multiple periods

Given the problems stated above and interlinked via the defection and tariff decision, respectively, and assuming an exogenous revenue cap, we can now investigate the network operator's tariff decision, given the households' best response. With that, we arrive at an equilibrium tariff and defection path for any revenue cap regulatory scheme.

[14] In the debate on the introduction of stricter regulation of district heating prices and or profits of the operators, this *natural* limit to prices due to the existence of an alternative inducing competition to the market is used as an argument against such regulation (Monopolkommission, 2024).

Network Tariff

Plugging in the households' best response (given in Definition 1) into the network operators' profit maximization problem, we see that

$$R_t = Q\tau_t(1-\tilde{\alpha}_t) = Q\tau_t\left(1 - \frac{Q\left(P_{\Delta,t}+\tau_t\right)}{\Delta I_{d,t}}\right),$$

i.e., the operator's revenue is quadratically dependent on the network tariff. This means two solutions to the network operators' problem given a revenue target. Both, a tariff of $\tau = 0$ and $\tau = \frac{\Delta I_{d,t} - QP_{\Delta,t}}{Q}$ yield a revenue of zero. In the following, we only consider the non-zero tariff to be used.

Assumption 2. *$\tau_t \leq \frac{\Delta I_{d,t} - QP_{\Delta,t}}{2Q}$, if $\tilde{RC}_t > 0$.*

As we will see later, $\frac{\Delta I_{d,t} - QP_{\Delta,t}}{2Q}$ constitutes the unregulated operator's tariff (see Corollary 13). Therefore, assumption 2 implies that the network tariff corresponding to any exogenous revenue cap set by the regulator is not larger than revenue realized through the unregulated operator's network tariff. If the revenue cap were higher than the unregulated operator's revenue, the operator would not attain this revenue cap as the operator anticipates the defection a tariff corresponding to that high revenue cap would induce. Hence, it is non-binding if the revenue cap set by the regulator $\tilde{\mathrm{RC}}_t$ is higher than the unregulated operator's attainable revenue. In our simple model, the network tariff is thus uniquely defined. Further notice that, due to its quadratic structure, R_t has a unique maximum. For ease of exposition, we define the effective revenue cap RC_t as the minimum of either the regulator's revenue cap or the apex of R_t.

Definition 3. *The Effective Revenue Cap is given by $RC_t = \min\{\tilde{RC}_t, \frac{(\Delta I_{d,t} - QP_{\Delta,t})^2}{4\Delta I_{d,t}}\}$.*

In other words, the effective revenue cap is the revenue cap that the operator is confronted with in their tariff design problem. Note that if $\Delta I_{d,t}$ is or is close to 0, households leave the network for any non-zero network tariff. Thus, in this case, the network operator's revenues go to zero for any exogenous revenue cap. Under this definition of RC_t, the effective revenue cap is always binding, and we can constitute the equilibrium condition of the tariff design decision:

$$Q\tau_t(1-\tilde{\alpha}_t(\tau_t)) = R_t \overset{!}{=} \mathrm{RC}_t. \tag{1}$$

Given the elaborations above, we the further assume:

Assumption 4. $\frac{RC_t}{RC_{t-1}} \leq \frac{\Delta I_{d,t} - QP_{\Delta,t}}{\Delta I_{d,t-1} - QP_{\Delta,t-1}} \leq 1.$

The effective revenue cap decays at least as fast as the difference between the benefit of waiting and the excess cost of using the incumbent good. Given the assumptions of decreasing defection cost and non-decreasing price difference, this means that the revenue cap must at least be non-increasing, which is a natural assumption for a network in decline. Based on this, we arrive at the equilibrium network tariff under revenue cap regulation, τ.

Proposition 5. $\tau_t = \frac{\Delta I_{d,t} - QP_{\Delta,t}}{2Q} - \sqrt{\left(\frac{\Delta I_{d,t} - QP_{\Delta,t}}{2Q}\right)^2 - \frac{RC_t \Delta I_{d,t}}{Q^2}}.$

The proof is provided in the Appendix. As the development of τ_t is directly linked to the trajectory of RC_t, no general statements can be made for τ_t. In chapter three, we will revisit the impact of different revenue caps on the τ_t trajectory.

Equilibrium Defection Path

Corresponding to the network tariff for each period t identified above, the hurdle rate characterizing the share of households that have defected to an alternative at time t, $\tilde{\alpha}_t$, can be derived.

Corollary 6. $\tilde{\alpha}_t = \frac{1}{2} + \frac{QP_{\Delta,t}}{2\Delta I_{d,t}} - \sqrt{\left(\frac{1}{2} - \frac{QP_{\Delta,t}}{2\Delta I_{d,t}}\right)^2 - \frac{RC_t}{\Delta I_{d,t}}}$; $\tilde{\alpha}_T = 1$,
where $0 \leq \tilde{\alpha}_t \leq 1$. *It holds* $0 \leq \Delta\tilde{\alpha}_t$.

Proof is provided in the Appendix. As shown in Corollary 6, $\tilde{\alpha}_t$ is increasing and can thus be interpreted as a defection trajectory. Therefore, under the stated assumptions, τ_t and $\tilde{\alpha}_t$ constitute an equilibrium path of defection. Considering the structure and composition of τ_t and $\tilde{\alpha}_t$ as derived above, our first conclusion is that the revenue cap influences both variables. Moreover, it is straightforward to see and intuitive that under the stated assumption and within the *natural* limitations of the revenue cap, a higher revenue cap induces a higher tariff and defection. More specific deductions of equilibrium tariffs and defection can only be drawn for specific revenue caps. We will thus investigate how different revenue cap strategies affect welfare through the associated defection trajectories.

2.3 Limitations of the approach

It should be noted that the presented approach has certain limitations. The inferences and results we discuss depend on the underlying assumptions.

Firstly, we assume a non-decreasing price difference, $P_{\Delta,t} - P_{\Delta,t-1} \geq 0$, which is central to the households' defection decision. Deviations from this assumption could lead to different defection outcomes. Different factors could influence this difference: the cost of heating with gas could be lower than expected, and the cost of heating with electricity higher. On the one hand, the anticipated increase in LNG capacity expected to come online in 2027 could lead to a decrease in natural gas prices (IEA, 2024). Similarly, cheaper gas could induce cheaper electricity as gas-fired power plants are often price-setting in European power markets. On the other hand, an increase in carbon prices, for instance, via the EU ETS II, could increase the cost of heating with gas. Similarly, the integration of renewable energy sources demands substantial investment in the grid, which could potentially increase household electricity costs. Accordingly, it is unclear how the different effects realize and shape the price difference per unit of heat in the upcoming years.Moreover, we assume that a household's heat demand remains unchanged after switching to the alternative technology. However, it may be more realistic to expect a shift in heat demand, Q, if the household invests in alternative technology and associated retrofits. A decrease in demand, while keeping price constant, effectively mirrors a reduction in price for a fixed demand, as the household's spending on electricity remains unchanged. Consequently, this shift in demand could be interpreted as a functional equivalent to a decrease in the electricity price. This could mitigate the risk of increasing electricity prices elaborated above. Generally, other defection outcomes could be explored using stochastic modeling. Secondly, we assume that the revenue cap is at least non-increasing. This assumption allows us to derive an analytically unique equilibrium solution for τ_t and $\tilde{\alpha}_t$. One can argue that this is a natural assumption for a network in decline in which no further investments are made. However, if this assumption does not hold, the network operator could charge an even higher tariff and defection would be more pronounced. Finally, we (implicitly) assume that the defection of households is purely driven by a cost-benefit analysis that leads to full defection in the final period. Note that if the price development for both technologies does not ensure such development, there will be a jump in the last period. Policy makers can anticipate this and influence the required price paths either by implementing a higher carbon price, which increases $P_{g,t}$ or a subsidized investment cost $I_{d,t}$.

3 The Regulator

The equilibrium developed above is contingent upon a revenue cap set by the regulatory authority, which can draw on different rationales to set them: The regulator, the third agent considered in the analysis, has to consider cost recovery for network operators and cost-minimization for households, thus structures the revenue cap accordingly. To facilitate a better understanding of the implications of different forms of revenue cap regulation, we will conduct a welfare analysis. Therefore, we will introduce the concept of welfare first and then derive the optimal revenue cap. In Section 4, we will compare the theoretical results to a stylized version of the status quo revenue caps implemented in several European countries such as Germany, Austria and Ireland.

3.1 Welfare

The total welfare considered here for the regulators' revenue cap design problem is composed of two elements: 1) the welfare effects within the network (*internal* welfare) and 2) the welfare effects of (the lack of) cost recovery (*external* welfare). The first considers the effects on welfare realized due to the defection path. Recall that higher tariffs, allowed by a higher revenue cap, induce premature defection compared to a lower revenue cap and, correspondingly, lower tariffs. The early defection corresponds to excessive social cost, since affected households, since they have to invest earlier, thus spend more. At the same time, the defection path affects the degree of cost recovery. Hence, the second welfare element considers the cost society realizes due to the non-recovery of fixed costs that range from increased capital costs for future investments in capital-intensive industries to the risk of non-provision of similar goods (other network infrastructure) due to absent investment. Their formalization is elaborated below.

3.1.1 Internal welfare effects

We first introduce the concept of the internal welfare effects, accruing within the network, which will then be tailored to the specific cases we will investigate. In line with standard economic theory, we consider welfare as the intertemporal sum of consumer and producer surplus. The consumer surplus is the difference of the willingness to pay, WTP_t, that households have for heat in t, regardless of the source and the cost realized from the consumption of heat in t. The producer surplus is the difference between the revenue generated and the fixed cost, κ, incurred through investments made into the grid.

Definition 7. *The internal welfare effects are given by*

$$\begin{aligned}
\boldsymbol{W}_I(\tilde{\alpha}_t) &= \underbrace{\sum_t^T \delta^t \left(WTP_t - \left[Q(P_{g,t} + \tau_t)(1 - \tilde{\alpha}_t) + QP_{e,t}\tilde{\alpha}_t + \frac{\eta^t I_d}{2} \left(\tilde{\alpha}_t^2 - \tilde{\alpha}_{t-1}^2 \right) \right] \right)}_{Consumer\ Surplus} \\
&\quad + \underbrace{\sum_t^T \delta^t \left[Q\tau_t(1 - \tilde{\alpha}_t) \right] - \kappa}_{Producer\ Surplus} \\
&= \sum_t^T \delta^t \left(WTP_t - QP_{g,t} \right) - \kappa + \sum_t^T \delta^t \left(Q\tilde{\alpha}_t P_{\Delta,t} - \frac{\eta^t I_d}{2} \left(\tilde{\alpha}_t^2 - \tilde{\alpha}_{t-1}^2 \right) \right) \\
&= \underbrace{\sum_t^T \delta^t \left(WTP_t - QP_{g,t} \right) - \kappa + \delta^T \left(QP_{\Delta,t} - \frac{\eta^T I_d}{2} \right)}_{const.} + \sum_t^{T-1} \delta^t \left(\tilde{\alpha}_t QP_{\Delta,t} - \frac{1}{2}\tilde{\alpha}_t^2 \Delta I_{d,t} \right)
\end{aligned}$$

The full derivation is provided in the appendix.

Note that the first part of the general welfare function is independent of the defection, $\tilde{\alpha}_t$, and the tariff, τ_t. As such it does not change under different revenue caps. To simplify the analysis and without loss of generality, it suffices to compare the second part of the stated welfare function across revenue cap cases. We define the reduced-form internal welfare accordingly.

Definition 8. *The reduced-form internal welfare is given by*

$$\omega_I(\tilde{\alpha}_t) = \sum_t^{T-1} \delta^t \left(\tilde{\alpha}_t QP_{\Delta,t} - \frac{1}{2}\tilde{\alpha}_t^2 \Delta I_{d,t} \right).$$

This expression will allow us to compare the effects of different revenue caps on internal welfare via the corresponding equilibrium defection path, $\tilde{\alpha}_t$.

3.1.2 External welfare effects

As we laid out before, the regulator might not only account for the welfare effects within the network, but also acknowledge the impact the results of the revenue cap might have beyond the market it regulates. As such, the regulator may account for the external effects (a lack of) cost recovery might have. We price the social value of cost recovery at λ.

Definition 9. *The external welfare effects are given by*

$$\omega_E(\lambda) = \lambda \left(\sum_t^{T-1} \delta^t \tilde{RC}_t - \kappa \right).$$

The external welfare is defined as the difference between the cumulative revenue caps over time, adjusted for the discount factor, and the investment costs incurred by the operator, scaled by the parameter λ representing the social value of cost recovery. In such a formulation, λ is often called the "shadow price of public funds" (cf. Boiteux, 1956). With the equilibrium path for household defection established, based on a given revenue cap, and a welfare measure that enables evaluation of the effects of various revenue caps, we can now derive the optimal revenue cap for a regulator aiming to maximize social welfare.

3.2 Optimal Revenue Cap

Standard economic theory suggests that (long-run) marginal cost pricing maximizes social welfare. For a *network in decline* with no need for further investment, marginal costs are effectively zero and thus translate into a revenue cap of zero. Under a revenue cap of zero, the tariff, τ, would also become zero, minimizing household costs for heating but leaving the network operator with no opportunity for cost recovery. Anticipating this revenue shortfall, the operator would lack the incentive to invest in the necessary infrastructure from the outset. For existing infrastructure built under the expectation of positive future cost recovery, the absence of positive tariffs could lead to significant externalities, resulting in social costs. Other operators may be deterred from investing in similar infrastructure in the future or face higher capital costs due to increased risk premia.

Consequently, the regulator's problem is maximizing the total welfare, composed of welfare effects both within and outside the network, i.e.,

$$\tilde{\mathrm{RC}}_t^O(\lambda) = \arg\min_{\tilde{\mathrm{RC}}_t} \underbrace{\sum_t^{T-1} \delta^t \left(\frac{1}{2}\tilde{\alpha}_t^2 \Delta I_{d,t} - \tilde{\alpha}_t Q P_{\Delta,t}\right)}_{-\omega_I(\tilde{\alpha}_t)} + \underbrace{\lambda\left(\kappa - \sum_t^{T-1} \delta^t \tilde{\mathrm{RC}}_t\right)}_{-\omega_E(\lambda)},$$
$$\text{s.t. } \tilde{\alpha}_t = \frac{1}{2} + \frac{QP_{\Delta,t}}{2\Delta I_{d,t}} - \sqrt{\left(\frac{1}{2} - \frac{QP_{\Delta,t}}{2\Delta I_{d,t}}\right)^2 - \frac{\tilde{\mathrm{RC}}_t}{\Delta I_{d,t}}}. \tag{2}$$

where $\tilde{\alpha}_t$, characterizing the set of households that have defected to an alternative, depends on $\tilde{\mathrm{RC}}_t$, the revenue cap set by the regulator, via the network operator's tariff decision. Accordingly, the stated maximization problem of the regulator yields a revenue cap that takes account of the tariff decision made by the operator and the defection decision made by the household. Recall Proposition 5 and Definition 1 that yield Corollary 6, stated here in the second line as a constraint. Where not necessary, we drop the dependency on λ for notational simplicity.

At a social cost of zero, $\lambda = 0$, for the non-recovery of fixed costs, we arrive at a traditional welfare maximization only accounting for internal welfare, i.e., the efficiency of defection decisions. Under non-zero social cost of missed recovery, however, this regulatory approach, usually termed *first-best*, would not generate any revenue for the network operator.[15] At a very high social cost of non-recovery of fixed costs, $\lambda \to \infty$, the regulator's problem mimics the revenue maximization of the operator as seen before; it would correspond to an unregulated network operator problem.

Proposition 10. *The welfare-optimal revenue cap is given by* $\tilde{RC}_t^O(\lambda) = \left(1 - (\frac{1}{1+2\lambda})^2\right) \frac{\left(\Delta I_{d,t} - QP_{\Delta,t}\right)^2}{4\Delta I_{d,t}} < \frac{(\Delta I_{d,t} - QP_{\Delta,t})^2}{4\Delta I_{d,t}}$, *where* $\tilde{RC}_t^O \leq \tilde{RC}_{t-1}^O$.

The proof is provided in the Appendix. The fact that the optimal revenue cap is non-increasing is an intuitive result: As the network assets depreciate, the revenue cap should be lowered, mirroring the reduced capital stock. We define $\overline{\lambda}$ as the price at which cost is completely recovered: $\kappa = \sum_t^{T-1} \delta^t R_t^O(\overline{\lambda})$. Note that in our simple specification, $\tilde{\mathrm{RC}}_t^O$, does not depend on the investment made in the past, represented by the capital stock that is indicated by κ. The role of κ is only indirect, as the cost of non recovery might be valued higher when κ is higher. We assume that in practical applications $\lambda \leq \overline{\lambda}$, such that cost recovery beyond κ is never socially optimal. We will, however, consider the case $\lambda \to \infty$ as an extreme case representing a lack of regulation.

The operator's problem can equivalently be interpreted as a maximization of internal welfare under a cost recovery constraint, where λ is the dual multiplier associated with the constraint (cf. Boiteux, 1956). Therefore, for any targeted degree of cost recovery, $\sum_t^{T-1} \delta^t R_t^O(\lambda)$, the optimal revenue cap maximizes internal welfare. Conversely, revenue cap strategies that deviate from the optimal approach outlined above result in reduced internal welfare while attempting to achieve an equivalent level of cost recovery. Given the optimal revenue cap, we can now investigate the associated equilibrium path of network tariffs and household defections.

Network Tariff

The network tariff design problem in this case is given by

$$\max_{\tau_t} \Pi = \sum_t^{T-1} R_t = \sum_t^{T-1} \delta^t Q\tau_t(1 - \tilde{\alpha}_t^*)$$
$$\text{s.t.} \quad Q\tau_t(1 - \tilde{\alpha}_t^*) \leq \tilde{\mathrm{RC}}_t^O(\lambda) = \left(1 - \left(\frac{1}{1+2\lambda}\right)^2\right) \frac{\left(\Delta I_{d,t} - QP_{\Delta,t}\right)^2}{4\Delta I_{d,t}}.$$

[15] We avoid the first-best, second-best, etc. terminology to emphasize the point that cost recovery may be an equally important goal for the regulator rather than a constraint.

Solving the stated problem, yields the optimal network tariff that is given by

Corollary 11. $\tau_t^O(\lambda) = \frac{\lambda}{1+2\lambda}\frac{\Delta I_{d,t}-QP_{\Delta,t}}{Q}$. *It is non-increasing in time, i.e.,* $\tau_t^O \leq \tau_{t-1}^O$.

Proof is provided in the Appendix.

Corollary 11 provides a significant result, as it shows that, similarly to the revenue cap, the optimal tariff is decreasing. The former is intuitive, as explained above. The latter, however, is not as straightforward. Even with a decreasing revenue cap, tariffs could increase depending on the speed of defection. Projections based on the current revenue cap regulation and estimations for grid defection show drastically increasing tariffs in the upcoming years (Rosenow, Lowes, & Kemfert, 2024). In contrast to these projections, we find that the optimal revenue cap and corresponding tariffs embody the principle of *front-loading*: The optimal revenue cap and tariffs are set higher in the initial periods and decrease over time. This approach moves cost recovery to a point in time when a larger share of households remains connected to the grid.

There are two special cases that have been briefly noted above already: (1) $\lambda = 0$ and (2) $\lambda \to \infty$. We write $\tau^O(\infty) = \lim_{\lambda\to\infty} \tau_t^O(\lambda)$ for the second. Using the term derived for the optimal tariff, we can plug in the respective λ and yield the optimal tariffs in each case. We arrive at

Corollary 12. *For* $\lambda = 0$, *the optimal network tariff is given by* $\tau_t^O(0) = 0$.

Corollary 13. *For* $\lambda \to \infty$, *the optimal network tariff is given by* $\tau_t^O(\infty) = \frac{\Delta I_{d,t}-QP_{\Delta,t}}{2Q}$.

The first corresponds to the highest internal welfare (traditional "first-best") as it minimizes household costs for heating. The second corresponds to the case of an unregulated network operator restricted by the choice of the tariff only by the household prospect to defect from the grid. The regulator therefore internalises the reaction of households so that the optimal RC always corresponds to the effective RC of the grid operator.

Equilibrium Defection Path

We can now deduce the households' defection path under optimal regulation.

Corollary 14. $0 \leq \tilde{\alpha}_t^O(\lambda) = \frac{\lambda}{1+2\lambda} + \frac{1+\lambda}{1+2\lambda}\frac{QP_{\Delta,t}}{\Delta I_{d,t}} \leq 1; \tilde{\alpha}_T^O = 1$. *It holds* $0 \leq \Delta\tilde{\alpha}_t^O$.

Proof. Follows from Definition 1 using Corollary 11. □

As per Definition 1, $\tilde{\alpha}_t^O$ is increasing and can thus be interpreted as a defection trajectory. Therefore, under the stated assumptions, with τ_t^O, $\tilde{\alpha}_t^O$ constitutes an equilibrium path of defection. For the two special cases considered above, the defection paths can be derived similarly:

Corollary 15. *For* $\lambda = 0$*:* $\tilde{\alpha}_t^O(0) = \frac{QP_{\Delta,t}}{\Delta I_{d,t}}$.

Corollary 16. *For* $\lambda \to \infty$*:* $\tilde{\alpha}_t^O(\infty) = \frac{1}{2} + \frac{QP_{\Delta,t}}{2\Delta I_{d,t}}$.

Consequently, a welfare optimal revenue cap that balances the cost minimization and profit maximization of households and the operator yields corresponding defection and tariff trajectories that are dependent on λ, the social cost of non-recovery. To facilitate a better understanding of the analytical elaborations presented above, we illustrate the results and their implications in a numerical case study below.

4 Numerical Case Study

We apply our findings in this section in a numerical case study. This allows us to elaborate on our results and additionally compare them with the status quo regulation in respect to cost recovery, internal welfare and distributional effects. Throughout this section, we use the parameters that are provided in Table 2 in the appendix.

Figure 1 shows the optimal revenue cap for different values of λ and the associated equilibrium paths. All figures reveal the space between the extremes described by the Corollaries 15 and 16.

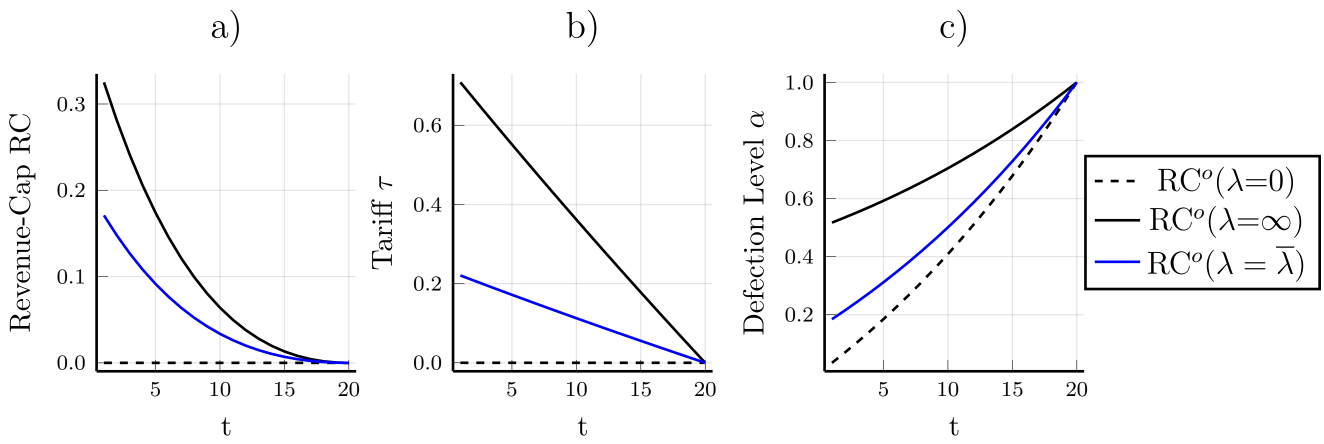

Figure 1: Optimal Revenue Caps and resulting Equilibrium Paths

Traditional first-best regulation with $\lambda = 0$ results in a revenue cap of 0 that implies $\tau_t^O = 0$, and thus $\tilde{\alpha}_t^O = \frac{QP_{\Delta,t}}{\Delta I_{d,t}}$. Therefore, $\tilde{\alpha}_t^O$ constitutes an equilibrium path of defection. The graph shows that defection is lowest for $\lambda = 0$. Note, with $\tau_t^O = 0$ in $\tilde{\alpha}_t^O$ the numerator is minimized and the denominator's value becomes relatively more significant in the ratio. $\tilde{\alpha}_t^O$ reduces to the Cost-Benefit-Ratio with which each household compares the cost of staying (nominator) to the benefit of waiting (denominator). Consequently, the household is effectively incentivized to delay its decision to defect or put differently, the household is less incentivized to defect prematurely, whereby the internal welfare in this case is maximized.

In the case of an (effectively) unregulated network operator, $\lambda \to \infty$, the operator is only bound by the prospect of households defecting from the grid. Correspondingly, with $\tau_t^O(\infty) = \frac{\Delta I_{d,t} - QP_{\Delta,t}}{2Q}$, $\tilde{\alpha}_t^0(\infty) = \frac{1}{2} + \frac{QP_{\Delta,t}}{2\Delta I_{d,t}}$ constitutes an equilibrium path of defection. Note, the additive constant shifts the entire expression for $\tilde{\alpha}_t^O(\infty)$ up by $\frac{1}{2}$ compared to the case of $\lambda = 0$. The tariff chosen by the operator is set such that more than half of all households defect from the grid immediately. Preventing these low relative cost types from defecting would require a network tariff that is lower than the stated one that maximizes the unregulated operator's profits.

Lastly, $\lambda = \overline{\lambda}$, results in what can be described as a convex combination of the previous two special cases elaborated above. All trajectories lie between the case of internal welfare maximization (lower bound) and the unregulated operators' profit maximization (upper bound). The same holds true for any $0 < \lambda < \infty$. Note $\lambda = \overline{\lambda}$ yields full cost recovery, while $\lambda = 0$ yields zero cost recovery and $\lambda \to \infty$ yields more than a break-even for the network operator as we will see in chapter 5.

The stylized example shown in the graphs clearly demonstrates the analytical results derived above. Front-loading is the optimal strategy for balancing defection and cost recovery. By setting a revenue cap that induces a front-loading tariff, the regulator can minimize the premature defection for any cost recovery goal, or vice versa, maximize cost recovery for any accepted internal welfare loss.

4.1 Comparison to Status Quo Regulation

In practice, assets used in revenue cap regulated industries are usually depreciated linearly over their commercial lifespan, with capital costs accounted for through regulated returns on capital (CEER, 2024). Using a stylized revenue cap, we can replicate the empirical projections by Rosenow, Barnes, and Galvin (2024) showing an increasing tariff and compare the implications to the optimal revenue cap identified above.

As a baseline case, we use a stylized revenue cap with linear depreciation of the capital stock κ over $\mathcal{T} = T + T_e$ years ($\Delta\kappa^{T+T_e} = \frac{\kappa}{T+T_e}$) and regulatory capital gains for the remaining capital stock in period t ($(\frac{1}{\delta} - 1)(\kappa - \frac{\kappa}{T+T_e}(t-1))$), i.e.,

$$\tilde{\text{RC}}_t^{LD}(T + T_e) = \Delta\kappa^{T+T_e} + \left(\frac{1}{\delta} - 1\right)\left(\kappa - \frac{\kappa}{T + T_e}(t - 1)\right).$$

T_e represents the extra commercial lifetime of the grid compared to the phase-out horizon. This depreciation period exceeds the remaining time until the phaseout is supposed to be completed, necessarily leading to incomplete sunk cost recovery, $\sum_{t=1}^{T-1} \delta^t \tilde{\text{RC}}_t^{LD}(T + T_e) < \kappa$. This stylized state of affairs mirrors the current state of the regulation in Germany, Ireland, Austria, the Netherlands, Australia, and the UK.

To increase cost recovery, it is currently discussed to shorten the depreciation period to the now expected end of operation. We implement this suggested regulatory intervention by shortening the depreciation period from $T + T_e$ to $T - 1$, i.e., $\sum_{t=1}^{T-1} \delta^t \tilde{\text{RC}}_t^{LD}(T - 1) = \kappa$.

Under linear depreciation over $\mathcal{T}$ periods, the equilibrium tariff and defection paths are then governed by

$$\tau_t^{LD}(\mathcal{T}) = \frac{\Delta I_{d,t} - QP_{\Delta,t}}{2Q} - \sqrt{(\frac{\Delta I_{d,t} - QP_{\Delta,t}}{2Q})^2 - \frac{\min\{\Delta\kappa^{\mathcal{T}} + (\frac{1}{\delta} - 1)(\kappa - \Delta\kappa^{\mathcal{T}}(t-1)), \frac{(\Delta I_{d,t} - QP_{\Delta,t})^2}{4\Delta I_{d,t}}\}\Delta I_{d,t}}{Q^2}},$$

$$\tilde{\alpha}^{LD}(\mathcal{T}) = \frac{1}{2} + \frac{QP_{\Delta,t}}{2\Delta I_{d,t}} - \sqrt{\left(\frac{1}{2} - \frac{QP_{\Delta,t}}{2\Delta I_{d,t}}\right)^2 - \frac{\min\{\Delta\kappa^{\mathcal{T}} + (\frac{1}{\delta} - 1)(\kappa - \Delta\kappa^{\mathcal{T}}(t-1)), \frac{(\Delta I_{d,t} - QP_{\Delta,t})^2}{4\Delta I_{d,t}}\}}{\Delta I_{d,t}}},$$

where $\mathcal{T} \in \{T + T_e, T - 1\}$ for the examples stated above. Note that while shortening the depreciation period to $\mathcal{T} = T - 1$ is supposed to increase the cost recovery of the network operator compared to the original depreciation period, it might not guarantee full cost recovery depending on the size of the remaining capital stock κ: If the net present value of the per-period revenue caps equals fixed cost, then fixed cost are only fully recovered if the revenue cap is not greater than the maximally attainable revenues for all periods, i.e.

$$\tilde{\text{RC}}_t \leq \frac{(\Delta I_{d,t} - QP_{\Delta,t})^2}{4\Delta I_{d,t}} \; \forall t = 1, ..., T-1.$$

Put differently, if the revenue caps and corresponding tariffs required for full cost recovery—enabled by accelerated depreciation—exceed the revenue that an unregulated operator would achieve, then full cost recovery becomes unattainable. This is because the operator does not set higher tariffs than those an unregulated operator would set, considering households increased incentive to defect prematurely when faced with higher costs.

To emphasize the point of limited cost recovery, we provide a brief numerical example, with the same parameters as given before, see Table 2 in the Appendix.

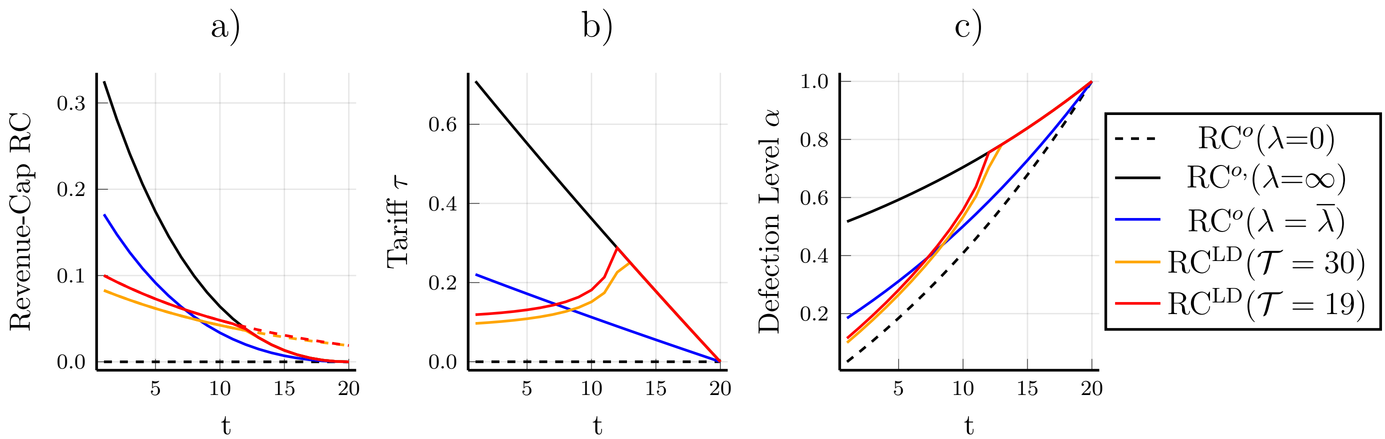

Figure 2: Revenue Caps and resulting Equilibrium Paths

Figure 2 illustrates the stylized linear depreciation options and allows for a comparison to the optimal trajectories discussed earlier. Recall that, under optimal regulation, both the tariff and revenue cap exhibit front-loading: they begin at relatively high levels and then gradually decline over time. In contrast, the stylized linear depreciation cases show revenue caps and tariffs moving in opposite directions. In both cases, the revenue caps exhibit front-loading. The only difference is that the revenue cap of the shortened period starts at a higher intercept than the original. However, when comparing them directly to the case $\lambda = \overline{\lambda}$, allowing for full cost recovery, they start at a lower level than the optimal revenue cap, and the slope of their decline is flatter. Accordingly, the front-loading is less pronounced than in the optimal case where the front-loading is degressive.

The equilibrium defection drives this enhanced front-loading. By acknowledging the household response, the operator can raise tariffs to maximize cost recovery over time, without tipping the system into a death spiral. In the status quo, the operator is constrained to the $\min\{\Delta\kappa^{\mathcal{T}} + (\frac{1}{\delta} - 1)(\kappa - \Delta\kappa^{\mathcal{T}}(t-1)), \frac{(\Delta I_{d,t} - QP_{\Delta,t})^2}{4\Delta I_{d,t}}\}$. Accordingly, the graph illustrates that until $t = 12$, the tariffs are driven by revenue cap, i.e., driven by κ and the expected years for depreciation. In $t = 12$, the revenue cap is larger than the unregulated operator's revenue. Recall that the household's response does not allow for a tariff that attains a larger revenue than the one realized by an unregulated operator. Therefore, subsequently, the tariff is guided by the household's response, i.e., $\tilde{\alpha}_{12+}$ is similar to $\tilde{\alpha}_t^{O}(\infty)$.

For the presented parameters and considering that the necessary tariff to achieve full cost recovery cannot be attained, in the status quo regulation, full cost recovery is impossible, unlike the case $\lambda = \overline{\lambda}$ under optimal revenue cap regulation.

The example critically illustrates the role of the household response in cost recovery, as it effectively limits the attainable tariff. This is especially important for policymakers and regulators in light of shortened operation times.

4.2 Internal Welfare & Cost Recovery

The illustration above shows that each revenue cap, status quo and optimal, induces different tariffs and, thus, different equilibrium defection paths. Accordingly, internal welfare effects and the degrees of cost recovery differ across the revenue cap cases. This subsections compare both and shows, that for a targeted cost recovery, the optimal revenue cap can attain this recovery at lower welfare losses as the status quo regulation. To identify the welfare implications of the five different revenue caps, we first compare the associated internal welfare. The highest internal welfare is achieved under optimal revenue cap regulation with $\lambda = 0$. In this case, households do not prematurely defect from the grid as their rationale is undistorted by a non-negative tariff. In all other cases of revenue caps, the tariff is positive and therefore inducing some premature defection. Hence, we define the change in internal welfare as the difference of the welfare achieved in each case from the case of maximized internal welfare with $\lambda = 0$. Put differently, we can define the internal welfare loss:

Definition 17. $\Delta\omega_I(\tilde{\alpha}_t) = \omega_I(\tilde{\alpha}_t) - \omega_I(\tilde{\alpha}_t^O(0))$.

To derive the differences in internal welfare for the defection paths discussed before. Plugging $\tilde{\alpha}_t^O(\lambda) = \frac{\lambda}{1+2\lambda} + \frac{1+\lambda}{1+2\lambda}\frac{QP_{\Delta,t}}{\Delta I_{d,t}}$ and $\tilde{\alpha}_t^O(0) = \frac{QP_{\Delta,t}}{\Delta I_{d,t}}$ into $\Delta\omega_I(\tilde{\alpha}_t)$, we find a general term for the internal welfare loss under optimal revenue regulation, only dependent on λ:

Definition 18.

$$\Delta\omega_I^O(\lambda) = -\sum_{t}^{T-1}\delta^t\left(\frac{1}{2}\left(\frac{\lambda}{1+2\lambda}\right)^2\frac{(\Delta I_{d,t} - QP_{\Delta,t})^2}{\Delta I_{d,t}}\right)$$

Similarly, the defection path can be derived under a linearly depreciating revenue cap. The result, though, does not readily provide an interpretable formulation; we thus omit the derivation here. Instead, we can derive the welfare loss induced by the previously illustrated set of parameters to discuss the differences between optimal and linearly depreciating revenue cap regulation. Figure 3, shows the cumulated internal welfare losses and cumulated revenues in the 5 cases. In the appendix, figure 5 shows the trajectory of this trade-off for different λ.

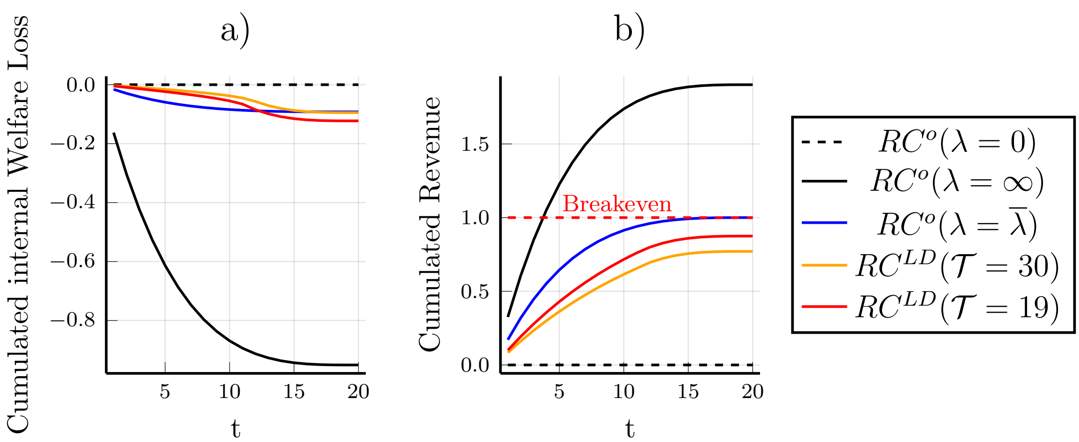

Figure 3: Internal welfare losses and revenues in the different settings.

The graphs in figure 3 mirror the previous results. The upper and lower bounds are again given by the revenue cap equal to zero and a non-binding revenue cap, the latter of which realizes the highest welfare loss and highest revenue. Again, the optimal revenue cap attaining full cost recovery lies between the two bounds. The cumulated internal welfare loss is displayed in a). Therein, the graph for the optimal revenue cap ($\lambda = \bar{\lambda}$) and the graphs for the linear depreciation cases lie closer to the revenue cap of zero ($\lambda = 0$). The welfare losses of the linear revenue caps display a flipped S-shape: They accumulate slowly in the beginning, then accelerate after the tenth period, only to slow down in the thirteenth period. The cumulated revenue for each case is presented in b). Here, for the time-shortened linear depreciation revenue cap, the accumulated revenue is higher than that of the non-shortened time frame. Yet, combining this with the trajectory of the cumulated welfare loss displayed on the left, we can say that this additional cost recovery comes at increased welfare losses. This displays the logic, although not endogenized in this structure, that increases in cost recovery induce losses in welfare. Interestingly, the linear depreciation revenue cap in the non-shortened time frame ultimately approximately yields the same cumulated welfare loss as the optimal revenue cap that attains full cost recovery. Yet, we observe that this welfare loss is associated with a smaller accumulated revenue compared to the optimal revenue that is established to achieve full cost recovery. In the appendix, figure 6 shows the predominance of optimal regulation for this trade-off in more detail.

4.3 Distributional Implications

As shown before, a positive tariff, τ, that allows for some degree of cost recovery reduces internal welfare. Recall that we introduced heterogeneous household types, $\boldsymbol{\theta}$. Accordingly, the effect of any positive tariff is not uniform across households. While each household compares the cost of staying to the benefit of waiting, the benefit of waiting differs among households as their investment costs are heterogeneous. Figure 4 shows the average excess cost, compared to a RC without cost recovery, for the household types ordered by $\alpha(\boldsymbol{\theta})$. We find that with optimal regulation, the households that can defect last are less burdened.

Because of the different times of defection, the cumulated cost for electricity, gas, τ and the investment differ. The latter is due to the compound effects of the learning rate and the discount factor playing out differently. The non-negative τ leads to earlier defection, thus resulting in savings for gas but higher spending as for electricity and more investment cost, since learning rate and discount factor have less impact, which is shown in a) and b). The high α type is associated with a higher reservation prices to switch, thus more inelastic to changes in τ. Hence, both cost recovering regulations are related to Ramsey–Boiteux pricing, since household types of high α pay more on a net balance.

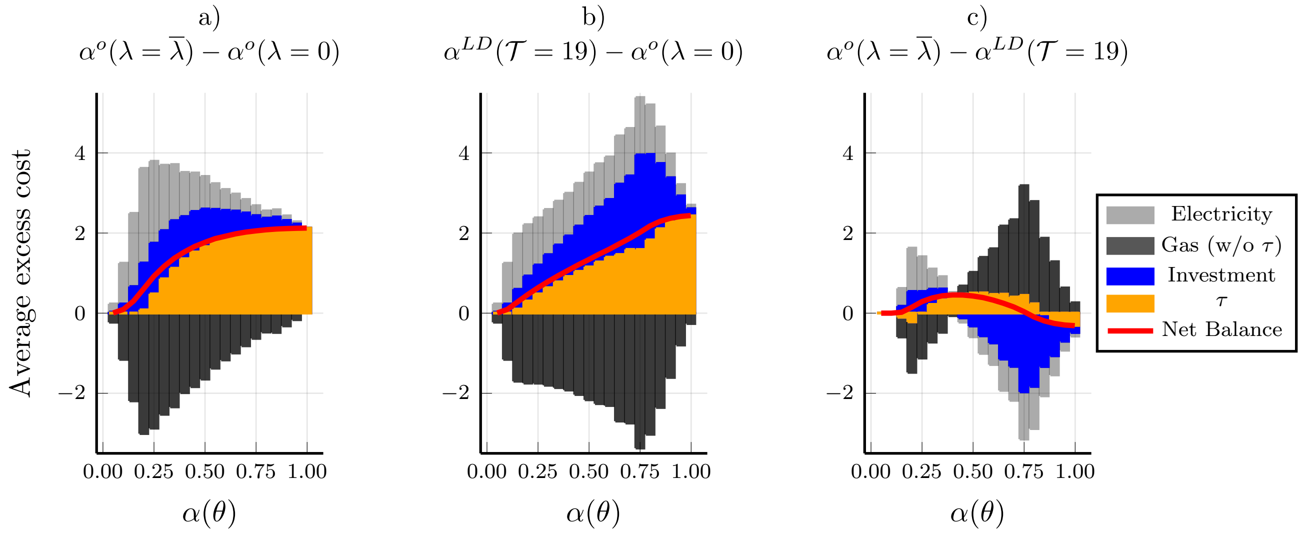

Figure 4: Comparison of excess cost for each type $\alpha(\theta)$

The comparison of the optimal revenue cap and the linear depreciation revenue cap in c) shows, that under the former, the 25% of households, which defect last, fare better compared to the linear depreciation revenue cap in the shortened time frame. Instead, the middle 15-75% of α types pay more, thus enabling the higher cost recovery for the network operator under the optimal revenue cap and allowing for some relief for the 25% of households. The 15% with the lowest relative defection cost, however, are left out from higher burden since they switch in the first period under both investigated revenue cap designs. Nevertheless, the optimal revenue cap scheme allows for a more even distribution of costs across households than the status quo scheme, as the higher tariffs in the earlier periods, which are shared by more households, allow for lower tariffs in the later periods for the remaining households that are most burdened.

5 Conclusion & Future Work

This paper investigates the welfare implications of different regulations in a regulated network in decline. It shows in great detail the trade-off between (internal) welfare losses for consumers and (external) welfare loss of non-cost recovery acknowledging the different tariff trajectories. It elucidates the interaction of tariffs and network defection when the network operator faces heterogeneous active consumers.

Using an equilibrium model, we examine different regulatory strategies and their effect on defection efficiency, cost recovery and ultimately welfare.

This paper identifies that degressive front-loading of revenue is an equilibrium strategy under optimal regulation but is also used by unregulated network operators. Moreover, a regulation inducing such front-loading yields lower welfare losses. This finding provides an analytical foundation for the empirical studies yielding the same result (Agora Energiewende, 2023; Oberle, 2023) and supports the policy recommendation of Rosenow, Lowes, and Kemfert (2024) to set appropriate depreciation rates. As an important contribution, this analysis demonstrates that incorporating household demand response is crucial when designing revenue caps to ensure a high degree of cost recovery. Moreover, the heterogeneity of circumstances of households must be considered to avoid an unequal allocation of the cost of this transition.

The social cost of incomplete cost recovery, indirectly represented by λ, is critical to locate the optimal revenue cap between the boundaries given by $\lambda = 0$, translating into a revenue cap of zero and $\lambda \to \infty$ translating into an unregulated operator, i.e., non-binding revenue cap. The choice of λ is a normative decision of the regulator.

When comparing the optimal revenue cap regulation for any social value of cost recovery λ to a stylized version of the status quo, we observe that while the revenue cap derived based on linear depreciation of the capital stock also is (slightly) front-loading, this is much less pronounced compared to the identified optimal regulation. This initially leads to lower tariffs, increasing to reach a maximum before dropping again toward the end of the defection horizon. As high network tariffs cannot be sustained toward the end of the time horizon, cost recovery generally remains incomplete, even for a shortened depreciation period. Only if κ is sufficiently low full cost recovery is possible. For any attained cost recovery, there is an optimal revenue cap, causing lower welfare losses.

The model in this work includes several simplifications and, hence, limitations. Yet, these simplifications are necessary for an analytically solvable model providing a clear intuition for the optimal regulatory approach. Let us highlight these limitations and elaborate on their implications Firstly, we assume any number of households can switch in any period. It is a much-discussed issue that the energy transition will require substantial capital and human resources. One concern is the limited availability of skilled workers, who, in our case, are needed to install the alternative technology in the home. Therefore, a further restriction such as $\tilde{\alpha}_t - \tilde{\alpha}_{t-1} \leq \gamma$, where γ is the maximum number of households that can switch in a period due to the constraint, could be introduced. This would lead to an optimal revenue cap design with even stronger front-loading in the first periods, as the network operator could take advantage of the household's situation, which would leave if only the workers and technology were available. Secondly, we assume household types are uniformly distributed. However, network operators often encounter more heterogeneous distributions of household types. Investigating other household distributions can reveal different outcomes. Thirdly, we assume a very simple representation of technological progress. The innovation literature provides several structures to consider learning in a model. One option for extension could be an endogenous learning rate dependent on the defection rate of households that could represent accelerated learning with increased adoption of the technology in contrast to our setup, where the learning rate declines exponentially. Fourthly, we refrained from including the investment decisions of the grid operator and only focused on the investments that were made in the past. Yet, exploring their investment decisions could reveal how additional investments might prolong grid connections and increase revenues. Fifthly, we assume that the value of the grid infrastructure in the last period is equal to zero and hence justify that full cost recovery can only be realized until then. However, there are ideas of alternative infrastructure uses, such as hydrogen or internet cables that may provide a new base of consumers and hence revenue. Investigating the implication of these alternatives for the revenue requirement and, hence, tariff decisions is another potential extension. Lastly, we assume there is no asymmetric information between the regulator and the network operator. In practice, the network operator might be more knowledgeable regarding the types of households in its network. Deriving an optimal regulatory approach accounting for this information asymmetry might be a worthwhile extension to capture the regulatory problem more realistically. To further develop the practical applicability of the front-loading of the optimal revenue cap, simplified approaches relying on less information could be investigated. As an example, a revenue cap with linear depreciation but an even further shortened depreciation horizon could approximate the optimal result reasonably well.

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A Appendix

A.1 Proof of Proposition 5, Network Tariff under Revenue Cap Regulation

Proof. Assume that $\tilde{\text{RC}}_t \leq \frac{(\Delta I_{d,t} - QP_{\Delta,t})^2}{4\Delta I_{d,t}}$ and note

$$\tilde{\text{RC}}_t \leq \frac{(\Delta I_{d,t} - QP_{\Delta,t})^2}{4\Delta I_{d,t}} \iff \left(\frac{\Delta I_{d,t} - QP_{\Delta,t}}{2Q}\right)^2 - \frac{\text{RC}_t \Delta I_{d,t}}{Q^2} \geq 0.$$

Then, the revenue that attains the revenue cap is given by

$$Q\tau_t^{RC}(1 - \frac{Q\left(P_{\Delta,t} + \tau_t\right)}{\Delta I_{dt}}) = \text{RC}_t$$

Using Assumption 2: $\tau_t \leq \frac{\Delta I_{d,t} - QP_{\Delta,t}}{2Q}$

$$\tau_t = \frac{\Delta I_{d,t} - QP_{\Delta,t}}{2Q} - \sqrt{\left(\frac{\Delta I_{d,t} - QP_{\Delta,t}}{2Q}\right)^2 - \frac{\tilde{\text{RC}}_t \Delta I_{d,t}}{Q^2}}.$$

If $\tilde{\text{RC}}_t > \frac{(\Delta I_{d,t} - QP_{\Delta,t})^2}{4\Delta I_{d,t}}$, then RC_t does not constrain the operator and the network operator cannot exhaust the revenue cap. Then,

$$\tau_t = \frac{\Delta I_{d,t} - QP_{\Delta,t}}{2Q} = \frac{\Delta I_{d,t} - QP_{\Delta,t}}{2Q} - \underbrace{\sqrt{\left(\frac{\Delta I_{d,t} - QP_{\Delta,t}}{2Q}\right)^2 - \left[\frac{(\Delta I_{d,t} - QP_{\Delta,t})^2}{4\Delta I_{d,t}}\right]\frac{\Delta I_{d,t}}{Q^2}}}_{=0}.$$

Combining both cases using Definition 3, we arrive at

$$\tau_t = \frac{\Delta I_{d,t} - QP_{\Delta,t}}{2Q} - \sqrt{\left(\frac{\Delta I_{d,t} - QP_{\Delta,t}}{2Q}\right)^2 - \frac{\text{RC}_t \Delta I_{d,t}}{Q^2}}.$$

□

A.2 Proof of Corollary 6, Equilibrium Defection Path

Proof. Recall $\tilde{\alpha}_t = \frac{Q(P_{\Delta,t}+\tau_t)}{\Delta I_{dt}}$ from Definition 1. Then

$$\tilde{\alpha}_t = \frac{Q\left(P_{\Delta,t} + \frac{\Delta I_{d,t}-QP_{\Delta,t}}{2Q} - \sqrt{\left(\frac{\Delta I_{d,t}-QP_{\Delta,t}}{2Q}\right)^2 - \frac{\mathrm{RC}_t \Delta I_{d,t}}{Q^2}}\right)}{\Delta I_{dt}}.$$

Rearranging yields

$$\tilde{\alpha}_t = \frac{1}{2} + \frac{QP_{\Delta,t}}{2\Delta I_{d,t}} - \sqrt{\left(\frac{1}{2} - \frac{QP_{\Delta,t}}{2\Delta I_{d,t}}\right)^2 - \frac{\mathrm{RC}_t}{\Delta I_{d,t}}}.$$

$0 \leq \Delta\tilde{\alpha}_t$ follows from Assumption 4. □

A.3 Derivation of Definition 7, Internal Welfare

To derive Definition 7, we rearrange the sum.

$$\begin{aligned}
\mathbf{W}_I(\tilde{\alpha}_t) &= \underbrace{\sum_t^T \delta^t \left(WTP_t - QP_{g,t}\right) - \kappa}_{A} + \sum_t^T \delta^t \left(Q\tilde{\alpha}_t P_{\Delta,t} - \frac{\eta^t I_d}{2}\left(\tilde{\alpha}_t^2 - \tilde{\alpha}_{t-1}^2\right)\right) \\
&= A + \sum_t^{T-1} \delta^t \left(Q\tilde{\alpha}_t P_{\Delta,T} - \frac{\eta^t I_d}{2}\left(\tilde{\alpha}_t^2 - \tilde{\alpha}_{t-1}^2\right)\right) + \delta^T \left(Q\tilde{\alpha}_t P_{\Delta,t} - \frac{\eta^T I_d}{2}\left(\underbrace{\tilde{\alpha}_T^2}_{=1} - \tilde{\alpha}_{T-1}^2\right)\right) \\
&= \underbrace{A + \delta^T \left(QP_{\Delta,t} - \frac{\eta^T I_d}{2}\right)}_{constant} + \underbrace{\sum_t^{T-1} \delta^t \left(Q\tilde{\alpha}_t P_{\Delta,T} - \frac{\eta^t I_d}{2}\left(\tilde{\alpha}_t^2 - \tilde{\alpha}_{t-1}^2\right)\right) + \frac{\delta^T \eta^T I_d}{2}\tilde{\alpha}_{T-1}^2}_{B}.
\end{aligned}$$

By using an index shift for the $\tilde{\alpha}_{t-1}$ term in B, we can write

$$\begin{aligned}
B &= \sum_t^{T-1} \delta^t \left(Q\tilde{\alpha}_t P_{\Delta,T} - \frac{\eta^t I_d}{2}\tilde{\alpha}_t^2\right) + \delta^{t+1}\frac{\eta^{t+1} I_d}{2}\tilde{\alpha}_t^2 \\
&= \sum_t^{T-1} \delta^t \left(Q\tilde{\alpha}_t P_{\Delta,T} - \frac{\eta^t I_d}{2}\tilde{\alpha}_t^2 + \delta\frac{\eta^{t+1} I_d}{2}\tilde{\alpha}_t^2\right) \\
&= \sum_t^{T-1} \delta^t \left(\tilde{\alpha}_t Q P_{\Delta,t} - \frac{1}{2}\tilde{\alpha}_t^2 \Delta I_{d,t}\right),
\end{aligned}$$

which completes the derivation.

A.4 Proof of Proposition 10, Welfare-Optimal Revenue Cap

Proof. $\mathrm{RC}_t^O(\lambda) = \big(1 - (\frac{1}{1+2\lambda})^2\big) \frac{\left(\Delta I_{d,t} - QP_{\Delta,t}\right)^2}{4\Delta I_{d,t}}$ follows directly from the operator's objective, Eq. (2), solving for $\tilde{\mathrm{RC}}_t^O$.

We assume that $0 \leq \lambda < \infty$, such that

$$\tilde{\mathrm{RC}}_t^O(\lambda) = \left(1 - \left(\frac{1}{1+2\lambda}\right)^2\right) \frac{(\Delta I_{d,t} - QP_{\Delta,t})^2}{4\Delta I_{d,t}} < \frac{(\Delta I_{d,t} - QP_{\Delta,t})^2}{4\Delta I_{d,t}} =: \tilde{\mathrm{RC}}_t^O(\infty).$$

With $P_{\Delta,t} \geq P_{\Delta,t-1}$ and $0 < \Delta I_{d,t} \leq \Delta I_{d,t-1}$, we see that

$$\begin{aligned}
&\underbrace{P_{\Delta,t-1}}_{\leq P_{\Delta,t}} \underbrace{\frac{\Delta I_{d,t}}{\Delta I_{d,t-1}}}_{\leq 1} \leq P_{\Delta,t} \\
\iff & \frac{QP_{\Delta,t-1}}{\Delta I_{d,t-1}} \leq \frac{QP_{\Delta,t}}{\Delta I_{d,t}} \\
\iff & 1 - \frac{QP_{\Delta,t}}{\Delta I_{d,t}} \leq 1 - \frac{QP_{\Delta,t-1}}{\Delta I_{d,t-1}} \\
\implies & \left(1 - \frac{QP_{\Delta,t}}{\Delta I_{d,t}}\right)^2 \leq \left(1 - \frac{QP_{\Delta,t-1}}{\Delta I_{d,t-1}}\right)^2 \\
\implies & \Delta I_{d,t} \left(1 - \frac{QP_{\Delta,t}}{\Delta I_{d,t}}\right)^2 \leq \underbrace{\Delta I_{d,t-1}}_{\geq \Delta I_{d,t}} \left(1 - \frac{QP_{\Delta,t-1}}{\Delta I_{d,t-1}}\right)^2 \\
\iff & \frac{(\Delta I_{d,t} - QP_{\Delta,t})^2}{\Delta I_{d,t}} \leq \frac{(\Delta I_{d,t-1} - QP_{\Delta,t-1})^2}{\Delta I_{d,t-1}} \\
\iff & \tilde{\mathrm{RC}}_t^O - \tilde{\mathrm{RC}}_{t-1}^O \leq 0.
\end{aligned}$$

Note that $R_t^O(\lambda) = \mathrm{RC}_t^O(\lambda) = \min\{\tilde{\mathrm{RC}}_t^O(\lambda), \frac{(\Delta I_{d,t} - QP_{\Delta,t})^2}{4\Delta I_{d,t}}\} = \tilde{\mathrm{RC}}_t^O(\lambda)$. □

A.5 Proof of Corollary 11, Optimal Network Tariff

Proof. The revenue cap is given by $\mathrm{RC}_t^O = \left(1 - \left(\frac{1}{1+2\lambda}\right)^2\right) \frac{\left(\Delta I_{d,t} - QP_{\Delta,t}\right)^2}{4\Delta I_{d,t}}$. With Proposition 5, it follows $\tau_t^O(\lambda) = \frac{\lambda}{1+2\lambda} \frac{\Delta I_{dt} - QP_{\Delta,t}}{Q}$.

With $P_{\Delta,t} \geq P_{\Delta,t-1}$ and $0 < \Delta I_{d,t} \leq \Delta I_{d,t-1}$, respectively,

$$\tau_t^O(\lambda) - \tau_{t-1}^O(\lambda) = \frac{\lambda}{1+2\lambda} \frac{\Delta I_{d,t} - \Delta I_{d,t-1} + QP_{\Delta,t-1} - QP_{\Delta,t}}{Q} \leq 0.$$

□

A.6 Numerical Example

Parameter	Value	Parameter	Value
$I_{d,t}$	75	$P_{\Delta,t}$	$\frac{t}{T}$
η	0.98	T	20
δ	0.95	T_e	10
κ	1.0	Q	1.0

Table 2: Network and Economic Parameters for the Graphical Example.

A.7 Equivalence of Perfect Foresight and Myopia

Under a central planner assumption, we can write the household sectors problem under perfect foresight as

$$\begin{aligned}
\tilde{\alpha}_t^* = \arg\min_{\tilde{\alpha}_t} \sum_{t=1}^{T-1} \delta^t \Bigg(& \int_{\tilde{\alpha}_{t-1}}^{\tilde{\alpha}_t} 2I_{d,t} \underbrace{\mathbb{E}[\theta_I | \alpha(\boldsymbol{\theta}) = \alpha_t]}_{\frac{\alpha_t}{2}} \, d\alpha_t \\
& + Q \left(\int_0^{\tilde{\alpha}_t} 2P_{e,t} \underbrace{\mathbb{E}[\theta_Q | \alpha(\boldsymbol{\theta}) = \alpha_t]}_{\frac{1}{2}} \, d\alpha_t + \int_{\tilde{\alpha}_t}^1 2(P_{g,t} + \tau_t) \underbrace{\mathbb{E}[\theta_Q | \alpha(\boldsymbol{\theta}) = \alpha_t]}_{\frac{1}{2}} \, d\alpha_t \right) \Bigg) \\
= \arg\min_{\tilde{\alpha}_t} \sum_{t=1}^{T-1} \delta^t & \left(\int_{\tilde{\alpha}_{t-1}}^{\tilde{\alpha}_t} \alpha_t I_{d,t} \, d\alpha_t + Q \left(\int_0^{\tilde{\alpha}_t} P_{e,t} \, d\alpha_t + \int_{\tilde{\alpha}_t}^1 (P_{g,t} + \tau_t) \, d\alpha_t \right) \right).
\end{aligned}$$

Solving the integrals and using $\Delta I_{d,t} = I_d(\eta^t - \delta\eta^{t+1})$ we can rearrange to

$$\tilde{\alpha}_t^* = \arg\min_{\tilde{\alpha}_t} \sum_{t=1}^{T-1} \delta^t \left(\frac{\Delta I_{d,t}}{2} (\tilde{\alpha}_t^2 - \tilde{\alpha}_{t-1}^2) + Q \left(P_{g,t} + \tau\right) (1 - \tilde{\alpha}_t) + Q P_{e,t} \tilde{\alpha}_t \right).$$

To solve for $\tilde{\alpha}_t$, we derive the first-order condition

$$\Delta I_{d,t} \tilde{\alpha}_t - Q \left(P_{g,t} + \tau\right) + Q P_{e,t} = 0 \quad \forall t,$$

such that

$$\tilde{\alpha}_t = \frac{Q \left(P_{g,t} + \tau - P_{e,t}\right)}{\Delta I_{d,t}} = \frac{Q \left(P_{\Delta,t} + \tau\right)}{\Delta I_{d,t}},$$

which is precisely the defection trajectory derived through myopic household decisions.

A.8 Welfare and Cost Recovery

This result is highlighted in figure 5. It plots the cumulated welfare loss in the final period T against the degree of cost recovery. Accordingly, $0 < \lambda < \bar{\lambda}$ provides the frontier-shaped line. The orange and red diamonds below the frontier present both linear depreciation revenue caps. Both cases only partially recover costs. The difference indicated in the graph illustrates that at the same level of cost recovery, the welfare loss is 97% or 84% higher in the linear depreciation compared to the optimal revenue cap. Put differently, at respective cost recovery levels, the welfare losses in the stylized status quo regulation result in welfare losses that are almost twice as high as for the optimal revenue cap.

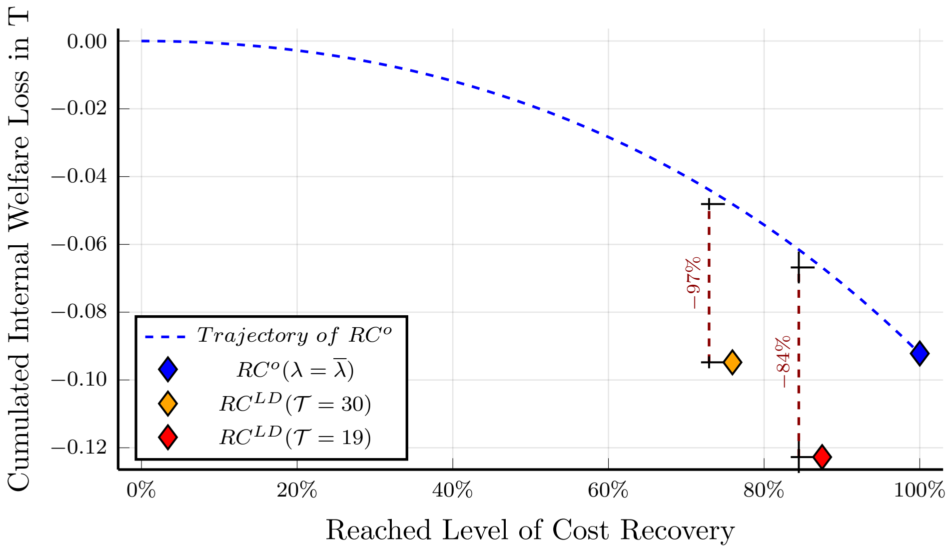

Figure 5: Welfare Effects depending on degree of Cost Recovery

Figure 6 shows that the greater the social cost of non-recovery, the larger the internal welfare losses. For the same fixed cost, the higher λ, the more premature defection occurs, increasing the accumulated welfare losses. The higher λ, the more weight the regulator gives to cost recovery, mitigating the associated social cost of non-recovery. Thus, tariffs increase, and defection speeds up accordingly. This is also reflected in the fact that the higher the cost of non-recovery, the more costs are ultimately recovered, since the welfare gains (mitigated losses) from cost recovery are relatively larger than the welfare gains achieved by cost minimization for households.

Ultimately, this comparison showcases, even if stylized, the challenge to full cost recovery of investments made in the past under the current regulation. Moreover, it highlights the cumulated welfare implications of the different revenue caps.

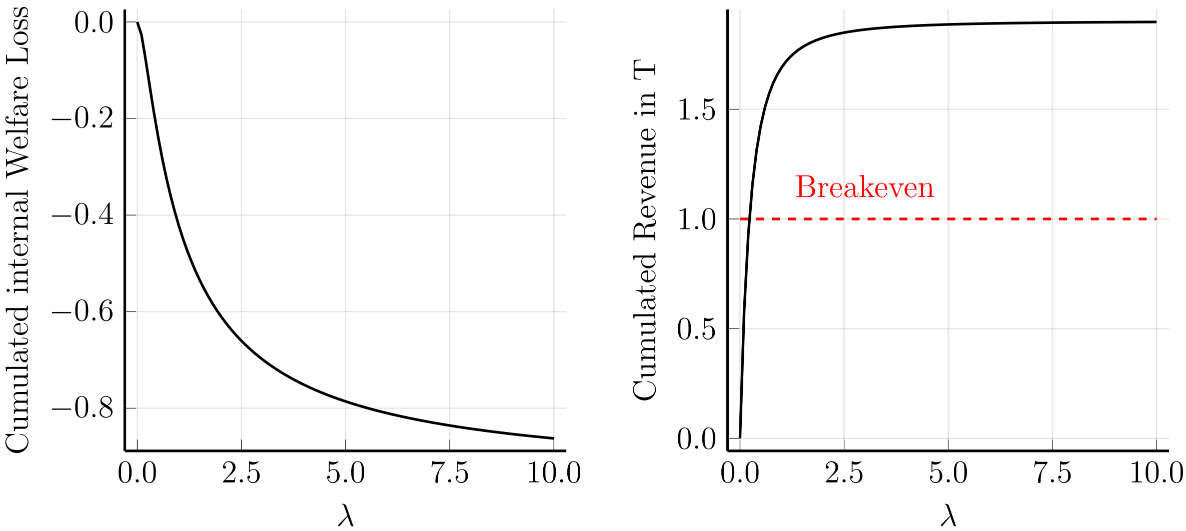

Figure 6: Welfare Effects depending on λ