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Revenue Cap Regulation in a Deregulated Electricity Market - Effects on a Grid Company

by

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– Effects on a Grid Company

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Abstract

In 1997 an incentive-based regulation was introduced for Norwegian transmission and distribution companies. Under the following revenue regulation regime, the permissible revenue of a grid company is adjusted annually, and during the first regulation period, the new revenue cap was determined on the basis of last year's revenue cap, adjusting for inflation, productivity improvement, and load growth. The idea behind the load growth compensation factor was that the grid companies should be compensated for increased costs due to grid expansion. Load growth was chosen, partly because it was considered to be an exogenously determined variable. However, in this paper, we will examine some investment incentives due to the load growth factor of the adjustment formula of the Norwegian regulation. We will show that as a result of parallel flows in electrical networks, a seemingly reasonable regulation policy of an electricity market may have paradoxical effects.

1. Introduction

Grid investments are normally carried out in electrical networks in order to achieve a well functioning integrated electricity market and/or to make the network more secure, i.e. less sensitive to link failures. In general, there are two aspects to be considered when making a new grid investment. The first is that of detecting beneficial investments and the second is how to induce them under the chosen market regime. In networks with adaptive routing it is well known that network "improvements", i.e. strengthening a line or building a new line, may in fact be detrimental to social surplus, and that some agents may have incentives to advocate these changes.

The revenue cap regulation for grid companies is part of the market regime. Accordingly, in this paper we will illustrate by means of simple numerical examples that a grid company, operating under a revenue cap regulation, may have incentives to invest in new lines that temporarily reduce transmitted energy. Hence, the incentive-based revenue regulation regime that was introduced in Norway can lead to a peculiar investment behavior.

2. The Norwegian Revenue Regulation Regime (1997-2001)

Since the Norwegian electricity market was deregulated in 1992, the operations of grid companies have been regulated, since they are operating in a monopoly market. Various schemes have been used, starting with a period of Rate-of-Return regulation, which later has been changed to a combination of an incentive-based and a performance-based regulation. Moreover, maximum and minimum returns on capital are determined, for 1997-2001, they were 15% and 2%, respectively, and these constitute additional constraints on the revenues. However, in this paper we will focus on the incentive-based revenue regulation, assuming that the maximum and minimum returns are not restrictive.

In the original revenue regulation scheme (NVE [23]), the initial revenue caps were determined on the basis of the grid companies' accounts from 1994 and 1995, i.e.

(2-1) $$IT_e = DV + AVS + AVK + NT\ ,$$

where IT_e is the initial revenue cap, determined by operating and maintenance costs (*DV*), depreciation (*AVS*), returns on invested capital (*AVK*) and costs associated with energy losses (*NT*). $NT = NT_{MWh} \cdot P$, where NT_{MWh} denotes losses in MWh, and P is the average system price of energy over the year in the Nord Pool spot market.

Annually, the revenue caps were adjusted for a general and an individual productivity factor, an inflation factor, and a growth factor for grid expansions. The formula for the revenue cap adjustment was

(2-2) $IT_{e,n+1} = \left[\left(IT_{e,n} - NT_n \right) \cdot \left(\frac{KPI_{n+1}}{KPI_n} \right) + NT_{MWh} \cdot P_{n+1} \right] \cdot (1 - EFK) \cdot (1 + 0.5 \cdot \Delta LE_{n+1,n})$,

where $IT_{e,n}$ is the revenue cap of year n, KPI is the inflation factor, represented by the consumer price index, EFK is the productivity improvement factor, and ΔLE is the relative increase in transmitted energy (loads plus losses). Notice that ΔLE is the *increase* in transmitted energy, expressed in percentages, and that a reduction in transmitted energy is not treated as a *negative* increase in transferred energy. Thus, $\Delta LE_{n+1,n} = \max\{0, (LE_{n+1} - LE_n) / LE_n\}$, and increases and reductions in transferred energy are not treated symmetrically.

One of the reasons for choosing load growth as an adjustment parameter, was that it was considered to be an exogenously given parameter. However, as pointed out by Grønli et al. [14] this factor "implies unpredictable and at times incidental compensation for grid expansion". This is not surprising since electricity networks work under an adaptive routing regime, and hence, the appearance of Braess' paradox (Braess [5]) can partly explain this unpredictability. In this paper we will look at the revenue cap formula as a part of the market mechanism design in a deregulated electricity market. Our focus is on the incentives inherent in this regulation formula, inducing the grid company to make "peculiar" grid investments in order to increase the revenue cap as much as possible.

3. Braess' Paradox

In user-optimizing traffic assignment problems, where each individual user is expected to choose the path with the lower travel cost, it is well known that the equilibrium flow in a network is generally different from the system optimal flow, minimizing total travel cost. In this setting, Braess [5] showed that adding a new road to a congested network might *increase* travel cost for all. This paradoxical effect is known as Braess' paradox, and is well studied in traffic networks. The reason for the traffic equilibrium paradoxes, is the behavioral assumption that a traveler chooses the path that is best for himself without paying attention to the effect this has on the other users (eventually including himself).

In user equilibrium, a user cannot decrease travel time by unilaterally changing his travel route, leading us to seeing the equilibrium as a Nash equilibrium of an underlying game. Korilis et al. [21] investigate the non-cooperative structure of certain networks, where the term non-cooperative emphasizes that the networks are "operated according to a decentralized control paradigm, where control decisions are made by each user independently, according to its own individual performance objectives". Nash equilibria are generally Pareto inefficient as is demonstrated by Dubey [13], and Korilis et al. use the Internet as an example, while referring more generally to queuing networks.

Cohen and Horowitz [11] give examples of Braess' paradox for other non-cooperative networks like mechanical systems (strings) and hydraulic and electrical networks, and point to the need for specifications of conditions, under which general networks behave paradoxically. This is partly provided by Calvert and Keady [9], and Korilis et al. [21] propose methods for avoiding degradation of performance, when adding resources to non-cooperative networks.

In the following sections, we will give examples of paradoxical situations that can occur in electrical networks due to electrons behaving "non-cooperatively", and how this, combined with a revenue cap adjustment formula including load growth, might lead to strange investment behavior from a grid company. The "non-cooperative" behavior of electrons is reflected in the power flow equations describing the load flows in the network (Dolan and Aldous [12]). As shown in Bjørndal and Jørnsten [3], the power flow equations can be seen as the first order conditions of an optimization problem. Hence, the optimal dispatch problem, that the market transactions are supposed to replicate, can be seen as a bilevel programming problem, consisting of an upper level program, which is the social maximization problem, and a lower level program, determining the underlying physical equilibrium. Consequently, the optimal dispatch problem is similar to Stackelberg leader-follower games or principal-agent problems.

When computing the economic equilibria, we assume competitive electricity markets, i.e. we do not consider gaming in the form of strategic bids. In that respect, our analysis follows the same line of research in electricity markets that was performed by Hallefjord et al. [15] for elastic traffic equilibria. Moreover, we assume that congestion, due to thermal capacity constraints in the grid, is managed by means of optimal nodal prices, although zonal pricing is actually used in the Norwegian scheduled (day-ahead) power market[1]. For a discussion of the Norwegian zonal pricing regime, see Bjørndal and Jørnsten [4]. Zonal pricing, which is an approximation of nodal pricing, requiring that prices are uniform within specified zones, cannot be expected to mitigate the incentive effects identified in this paper.

Since we are dealing with investments in a network with adaptive routing, we should note the similarity to the network design problem in traffic networks, which has been well studied. (See for instance the network design model of LeBlanc [22], and the recent surveys of Yang et al. [31], and Yang and Bell [32]). It should be pointed out that the network design problem in adaptive networks is notoriously difficult, partly due to the fact that this problem is bilevel in nature and includes discrete variables.

4. Grid Investments in Electricity Networks

In the following examples, we will use the "DC" approximation of the power flow equations (Wood and Wollenberg [28]). This is the typical approximation used when conducting economic analyses on a congested power grid, and the assumptions behind are reasonable during the normal operations of a power grid. The "DC" approximation implies a linearization of the highly nonlinear equations describing the (parallel) flows of an alternating current network, and it allows us to ignore losses and to focus on real power only. Moreover, assuming a "well-behaving" objective function, the resulting social welfare maximization problem, i.e. the optimal dispatch problem, is convex, which is a prerequisite for the existence of an efficient market mechanism to replicate social optimum.

Example 1

Wu et al. [30] show a 3-node example where strengthening a line (by increasing its admittance) may lead to larger minimum cost. The network and initial optimal dispatch, with injections in nodes 1 and 3 and withdrawal in node 2, are displayed in Figure 4-1. In optimal

[1] Suggestions for different mechanisms for managing congestion can be found in for instance Schweppe et al. [25], Harvey et al. [16], Hogan [17], Chao and Peck [10], and Wu and Varaiya [29].

dispatch the nodal prices will be related by $p_1 < p_2 < p_3$ since line 1-3 is assumed to be congested in direction from node 1 to node 3 (for an argument, see Wu et al.). If the admittance of line 2-3 is increased, the power flow equations change, and flow will increase on path 1-3-2 if injections are maintained. This will result in line 1-3 becoming overloaded, and injection in the lower priced node 1 must be reduced in order to satisfy the capacity constraint of 5 units on line 1-3. Hence, by increasing the admittance, the former feasible power flow becomes *infeasible*, and this can be viewed as the physical paradox that results from the underlying physical equilibrium model. If consumption is to be maintained, injection in node 3 must increase, leading to larger minimum cost. Hence, an economic paradox occurs, that is the result of the underlying characteristics of the physical equilibrium model.

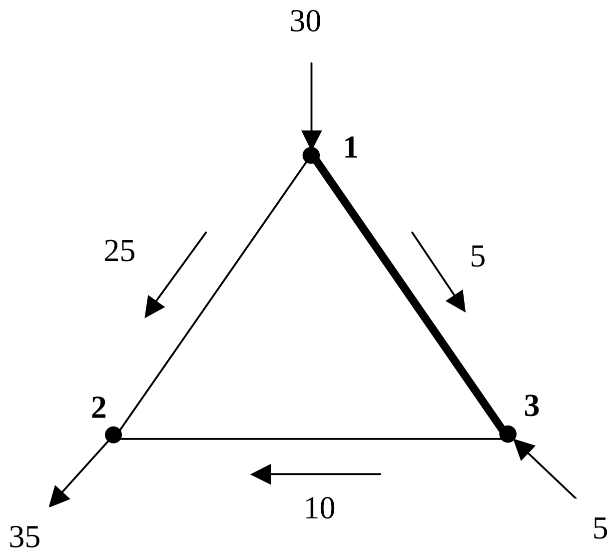

Figure 4-1 Increasing Admittance Increases Cost

Example 2

In a similar 3-node example, exhibited in Figure 4-2, Bushnell and Stoft [6] show that a new line hurts the network but still collects congestion rent. In the example, there is high cost production in node 1 and relatively lower cost production in node 2. Consumption takes place in node 3 where there is a fixed demand equal to 900 MW. Initially, there are only two links, 1-3 and 2-3, each with a capacity of 1000 MW, and demand is supplied entirely by the low cost producers in node 2.

In part B of Figure 4-2, a new line has been built between nodes 1 and 2. This is a weak line with a capacity of only 100 MW, and it introduces loop flow (parallel flows), having as a consequence that the transfer capacity between nodes 2 and 3 is greatly reduced. Assuming identical electrical characteristics on every link, and no production in node 1 to generate counter flow on line 1-2, it is reduced from 1000 to 300 MW. This is because $\frac{1}{3}$ of the power injected in node 2 will flow over the longer path 2-1-3, whereas $\frac{2}{3}$ will take the direct path 2-3. By inducing injections in node 1, the minimum cost of supplying 900 MW to node 3 is obtained by injecting 600 MW in node 2 and 300 MW in node 1, which is obviously a more costly dispatch.

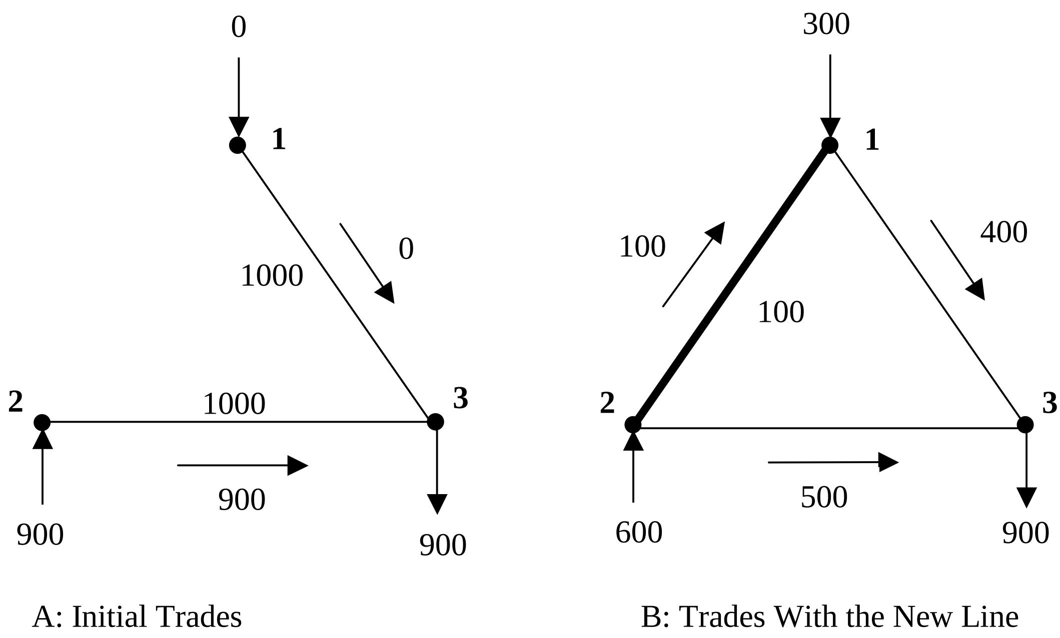

Figure 4-2 New Line Increases Cost

The grid revenue is normally defined as the merchandizing surplus, which is equal to

(4-1) $$MS = -\sum_{i=1}^{n} p_i q_i = \tfrac{1}{2}\sum_{i=1}^{n}\sum_{k=1}^{n}(p_k - p_i)\cdot q_{ik} \ ,$$

where p_i is the price in node i, q_i is net injection in node i (< 0 if there are net withdrawals from the node), and q_{ik} is the flow over line ik in direction from i to k. In part B of Figure 4-2, the new line is congested in direction from node 2 to node 1, and since $p_1 > p_2$, the new line receives congestion rent, providing grid owners with incentives to invest in a link that increases cost (even without considering the investment cost of the new link[2]).

The merchandizing surplus corresponds to the revenue from capacity charges in the central grid (Statnett [26]). However, capacity charges (which together with charges for losses and fixed charges constitute the revenues of the central grid) have no direct influence on the revenues of the *grid owners* like Statnett, the system operator of the Norwegian grid, and the major grid owner in the transmission network. This is because the revenues of the grid owners are determined by the revenue caps, implying that if a grid owner takes some action to increase capacity charges, it will not necessarily increase revenue.

Example 3

In Bjørndal and Jørnsten [2], we show that even with supply and demand present in every node, and demand being elastic, it is easy to find instances where a new line reduces social surplus and increases the merchandizing surplus. One example is given in Figure 4-3, where a new line is built between nodes 2 and 4, and line 1-2 is congested. In Figure 4-3 optimal nodal prices, p_i, net injections[3], q_i, and line flows are displayed.

Transmitted energy is equal to the sum of net withdrawals (or net injections, since we have assumed a lossless network). Before the new line between nodes 2 and 4 is introduced, transmitted energy (or power) is equal to $58.529 + 10.123 = 21.717 + 46.935 = 68.652$. After the new line is in place, this number is reduced to 53.727. Consequently, the merchandizing surplus increases due to the new line, while social surplus and transmitted energy is reduced, i.e. by making changes to the grid topology we may alter one of the determinants of the revenue cap. Hence, given a revenue cap regulation that includes a load growth factor, the grid company may have incentives to suggest an investment that reduces the load. Such an investment will have no negative effect on the revenue cap since only load *growth* is

[2] Grid owners could argue in favor of the new link, for instance because it improves on the security of the system. In case of a link failure on 1-3 or 2-3, the grid is still connected when line 1-2 is present.
[3] Net withdrawals are indicated by negative numbers.

accounted for, and a temporary load decrease will not affect the revenue cap negatively. The reason why a grid company has incentives to suggest such an investment is that when, in the future period, a new grid investment is being made, the load growth is measured from a lower basis. This makes the load growth adjustment factor larger and the revenue cap larger.

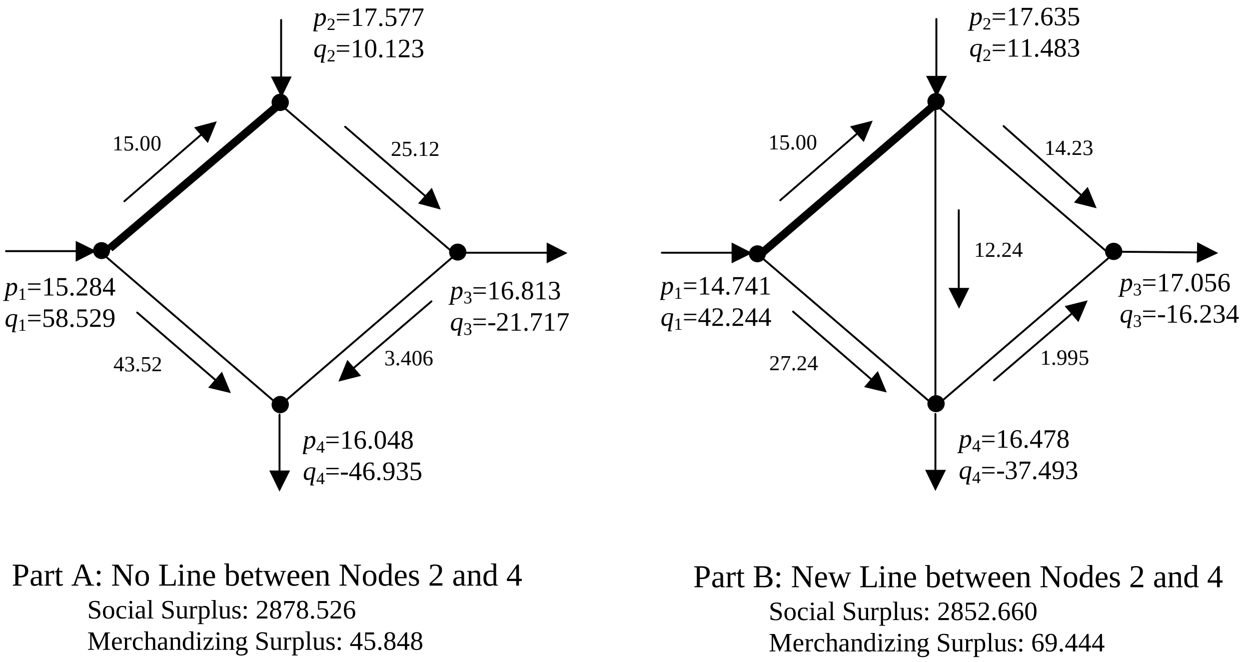

Figure 4-3 Optimal Dispatch before and after Line 2-4

5. Grid Investments and Revenue Caps

In the following, we will give an example of how a strategic investment in new lines can increase the revenue cap by exploiting the fact that increases and reductions in transmitted energy are not treated symmetrically in the revenue cap adjustment formula (2-2). Our example is a 6-node network with 4 possible new links, A, B, C and D, like the grid in Figure 5-1. We assume that all four links are to be installed in the original radial structure, but only one link is built in every period. This means that for a 4-period/4-link investment problem we have $4 \cdot 3 \cdot 2 \cdot 1 = 24$ different network expansion paths, depending on the sequencing of the link-investments. All four links are to be installed, and we will ignore investment costs. Moreover, since we have chosen to focus on a factor adjusting for increases in transmitted energy, we assume losses, inflation and productivity requirements equal to zero. In the regulation, revenue caps are determined based on *anticipated* load growth, and are then adjusted ex post for differences between anticipated and realized growth. In the example, we assume that anticipated is equal to actual load growth, so there will be no adjustments for forecasting errors.

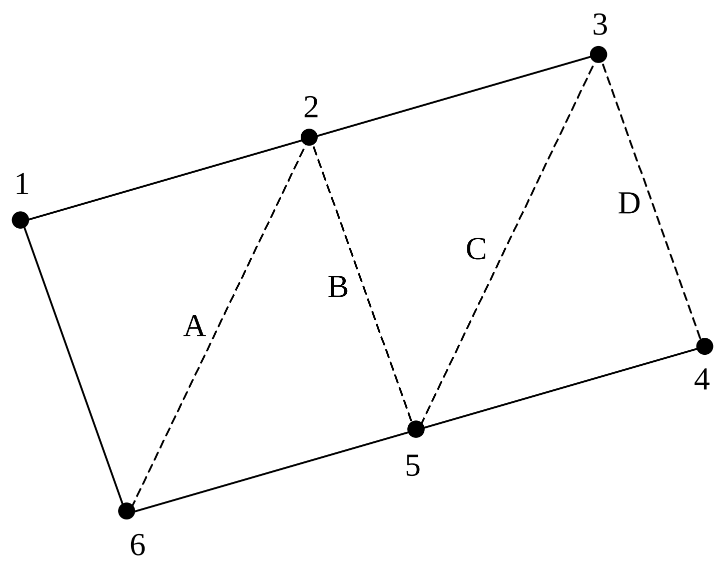

Figure 5-1 Grid with 4 Investment Opportunities

Each node in the network is assumed to have elastic demand and supply. If we assume impedances equal to 1 for each line, and that the lossless linear "DC" approximation, focusing on real power, still applies, optimal dispatch and optimal nodal prices are computed from the convex mathematical program:

(5-1) $$\max \sum_{i=1}^{n}\left(\int_{0}^{q_i^d} p_i^d(q)dq - \int_{0}^{q_i^s} p_i^s(q)dq\right)$$

(5-2) $$\text{s.t.} \quad q_i^s - q_i^d = \sum_{j \neq i} q_{ij} \qquad i = 1,\ldots,n-1$$

(5-3) $$\sum_{ij \in L_l} q_{ij} = 0 \qquad l = 1,\ldots,m-n+1$$

(5-4) $$\sum_{i=1}^{n}(q_i^s - q_i^d) = 0$$

(5-5) $$q_{ij} \le C_{ij} \qquad 1 \le i, j \le n,$$

where n is the number of nodes in the network, m is the number of links, $p_i^d(q_i^d)$ is the demand function of node i, q_i^d is the quantity of real power consumed in node *i*, $p_i^s(q_i^s)$ is the supply function of node i, and q_i^s is the quantity of real power produced in node *i*. C_{ij} is the capacity of link ij, and q_{ij} is the power flow over the link from i to j.

The objective function (5-1) expresses the difference between consumer benefit (the area under the demand curve) and the cost of production (the area under the supply curve). Equations (5-2) correspond to Kirchhoff's junction rule[4], and there are $n-1$ independent equations. Equations (5-3) follows from Kirchhoff's loop rule[5], where $L = (L_1, \ldots, L_{m-n+1})$ represents a set of independent loops (Dolan and Aldous [12]), and L_l is the set of directed arcs in a path going through loop *l*. Equation (5-4) stands for conservation of energy, while inequalities (5-5) are the capacity constraints.

For simplicity, we assume linear cost and demand functions, represented by $p_i = c_i q_i^s$ and $p_i = a_i - b_i q_i^d$ where p_i is the price in node *i*, and a_i, b_i and c_i are positive constants. Input data for our numerical experiment is given in Table 5-1.

Table 5-1 Input Parameters

NODE	CONSUMPTION		PRODUCTION
	a_i	b_i	c_i
1	20	0.05	0.1
2	20	0.05	0.6
3	20	0.05	0.1
4	20	0.05	0.4
5	20	0.05	0.5
6	20	0.05	0.4

[4] Kirchhoff's junction rule says that the current flow into any node is equal to the current flowing out of it.
[5] Kirchhoff's loop rule says that the algebraic sum of the potential differences across all components around any circuit or cycle is zero.

We will assume supply and demand parameters to be constant over the 4 periods, and that lines 1-6, 2-3 and the new line D have limited capacities, each equal to 20 units. The capacities of the other lines are assumed to be non-restrictive in the solutions.

In Table 5-2, we show the social surplus for each period and for each grid expansion path. Period 0 corresponds to the initial state of the network, i.e. the radial network without any of the new lines installed. In period 1, one additional link is installed, which link depends on the expansion path. In period 2, a second additional link is installed, etc. The different expansion paths are numbered as follows:

1	A-B-C-D	2	A-B-D-C	3	A-C-B-D	4	A-C-D-B	5	A-D-B-C	6	A-D-C-B
7	B-A-C-D	8	B-A-D-C	9	B-C-A-D	10	B-C-D-A	11	B-D-A-C	12	B-D-C-A
13	C-A-B-D	14	C-A-D-B	15	C-B-A-D	16	C-B-D-A	17	C-D-A-B	18	C-D-B-A
19	D-A-B-C	20	D-A-C-B	21	D-B-A-C	22	D-B-C-A	23	D-C-A-B	24	D-C-B-A

As can be seen from the numbers in Table 5-2, total social surplus for each period does not vary a lot, the difference between the highest and lowest surplus being less than 3%.

Table 5-2 Social Surplus

	0	1	2	3	4
1	4475.407	4453.466	4465.225	4543.497	4564.998
2	4475.407	4453.466	4465.225	4522.268	4564.998
3	4475.407	4453.466	4547.967	4543.497	4564.998
4	4475.407	4453.466	4547.967	4564.399	4564.998
5	4475.407	4453.466	4516.537	4522.268	4564.998
6	4475.407	4453.466	4516.537	4564.399	4564.998
7	4475.407	4481.369	4465.225	4543.497	4564.998
8	4475.407	4481.369	4465.225	4522.268	4564.998
9	4475.407	4481.369	4551.747	4543.497	4564.998
10	4475.407	4481.369	4551.747	4572.917	4564.998
11	4475.407	4481.369	4535.614	4522.268	4564.998
12	4475.407	4481.369	4535.614	4572.917	4564.998
13	4475.407	4550.234	4547.967	4543.497	4564.998
14	4475.407	4550.234	4547.967	4564.399	4564.998
15	4475.407	4550.234	4551.747	4543.497	4564.998
16	4475.407	4550.234	4551.747	4572.917	4564.998
17	4475.407	4550.234	4572.432	4564.399	4564.998
18	4475.407	4550.234	4572.432	4572.917	4564.998
19	4475.407	4532.775	4516.537	4522.268	4564.998
20	4475.407	4532.775	4516.537	4564.399	4564.998
21	4475.407	4532.775	4535.614	4522.268	4564.998
22	4475.407	4532.775	4535.614	4572.917	4564.998
23	4475.407	4532.775	4572.432	4564.399	4564.998
24	4475.407	4532.775	4572.432	4572.917	4564.998

In Table 5-3, we show transmitted energy for the different periods along the different expansion paths. Contrary to total social surplus, the variations are quite large, ranging from 64.089 to 113.727, a difference of 77.5%. We also see that some expansion paths show considerable fluctuations in energy transmitted, and this will affect the development of the revenue caps.

Table 5-3 Transmitted Energy

	0	1	2	3	4
1	84.516	64.089	68.491	96.401	106.498
2	84.516	64.089	68.491	84.780	106.498
3	84.516	64.089	100.568	96.401	106.498
4	84.516	64.089	100.568	106.614	106.498
5	84.516	64.089	83.887	84.780	106.498
6	84.516	64.089	83.887	106.614	106.498
7	84.516	85.286	68.491	96.401	106.498
8	84.516	85.286	68.491	84.780	106.498
9	84.516	85.286	107.436	96.401	106.498
10	84.516	85.286	107.436	113.691	106.498
11	84.516	85.286	96.272	84.780	106.498
12	84.516	85.286	96.272	113.691	106.498
13	84.516	108.581	100.568	96.401	106.498
14	84.516	108.581	100.568	106.614	106.498
15	84.516	108.581	107.436	96.401	106.498
16	84.516	108.581	107.436	113.691	106.498
17	84.516	108.581	113.727	106.614	106.498
18	84.516	108.581	113.727	113.691	106.498
19	84.516	99.160	83.887	84.780	106.498
20	84.516	99.160	83.887	106.614	106.498
21	84.516	99.160	96.272	84.780	106.498
22	84.516	99.160	96.272	113.691	106.498
23	84.516	99.160	113.727	106.614	106.498
24	84.516	99.160	113.727	113.691	106.498

In the tables below, we assume an initial revenue of 1 in period 0. The four tables show how the revenue cap develops for each period along each of the 24 different expansion paths. The revenue caps are adjusted for one half of the percentage *increase* in transmitted energy, according to formula (2-2). Since there is no adjustment for *decreases* in transmitted energy, and since we ignore productivity requirements, the revenue caps cannot be reduced from one period to the next along the same expansion path.

Revenue: Period 1

1 1.000,	2 1.000,	3 1.000,	4 1.000,	5 1.000,	6 1.000
7 1.005,	8 1.005,	9 1.005,	10 1.005,	11 1.005,	12 1.005
13 1.142,	14 1.142,	15 1.142,	16 1.142,	17 1.142,	18 1.142
19 1.087,	20 1.087,	21 1.087,	22 1.087,	23 1.087,	24 1.087

Revenue: Period 2

1 1.034,	2 1.034,	3 1.285,	4 1.285,	5 1.154,	6 1.154
7 1.005,	8 1.005,	9 1.135,	10 1.135,	11 1.069,	12 1.069
13 1.142,	14 1.142,	15 1.142,	16 1.142,	17 1.169,	18 1.169
19 1.087,	20 1.087,	21 1.087,	22 1.087,	23 1.166,	24 1.166

Revenue: Period 3

1 1.245,	2 1.157,	3 1.285,	4 1.323,	5 1.161,	6 1.311
7 1.209,	8 1.124,	9 1.135,	10 1.168,	11 1.069,	12 1.166
13 1.142,	14 1.177,	15 1.142,	16 1.176,	17 1.169,	18 1.169
19 1.092,	20 1.234,	21 1.087,	22 1.185,	23 1.166,	24 1.166

Revenue: Period 4

1 1.310,	2 1.306,	3 1.352,	4 1.323,	5 1.309,	6 1.311
7 1.273,	8 1.268,	9 1.194,	10 1.168,	11 1.206,	12 1.166
13 1.202,	14 1.177,	15 1.202,	16 1.176,	17 1.169,	18 1.169
19 1.232,	20 1.234,	21 1.226,	22 1.185,	23 1.166,	24 1.166

The maximal revenue cap in period 4, equal to 1.352, is obtained using expansion path 3, i.e. investing in link A in the first period, C in the second, B in the third, and finally D in the last period. This is contrasted with the revenue cap of 1.166 of expansion path 23, investing consecutively in links D, C, A and B. Thus, the revenue cap following from choosing the best investment sequence for the grid company is 13.76% higher than those of the inferior sequences (23, 12, and 24). Comparing the total revenues over the 4 periods (discounting by 7% per period in the summation) gives similar differences between the best (4) and worst (11) expansion path. The exact numbers are displayed below.

Total revenue over 4 periods, discounted by 7%

1 3.854,	2 3.779,	3 4.137,	4 4.146,	5 3.889,	6 4.013
7 3.774,	8 3.701,	9 3.768,	10 3.775,	11 3.666,	12 3.714
13 3.915,	14 3.924,	15 3.915,	16 3.922,	17 3.936,	18 3.936
19 3.797,	20 3.913,	21 3.787,	22 3.836,	23 3.876,	24 3.876

When the revenue cap regulation has been commented on by the industry, there has been a certain interest in increasing the compensation factor for increases in transmitted energy, see for instance Statnett [27]. This is, of course, not surprising. In the tables below, we show the development of the revenue cap when the adjustment factor for load growth is equal to 1 (instead of 0.5) in formula (2-2) i.e. if the revenue cap is adjusted for the whole increase in transmitted energy.

Revenue: Period 1

1 1.000,	2 1.000,	3 1.000,	4 1.000,	5 1.000,	6 1.000
7 1.009,	8 1.009,	9 1.009,	10 1.009,	11 1.009,	12 1.009
13 1.285,	14 1.285,	15 1.285,	16 1.285,	17 1.285,	18 1.285
19 1.173,	20 1.173,	21 1.173,	22 1.173,	23 1.173,	24 1.173

Revenue: Period 2

1 1.069,	2 1.069,	3 1.569,	4 1.569,	5 1.309,	6 1.309
7 1.009,	8 1.009,	9 1.271,	10 1.271,	11 1.139,	12 1.139
13 1.285,	14 1.285,	15 1.285,	16 1.285,	17 1.346,	18 1.346
19 1.173,	20 1.173,	21 1.173,	22 1.173,	23 1.346,	24 1.346

Revenue: Period 3

1 1.504,	2 1.323,	3 1.569,	4 1.664,	5 1.323,	6 1.664
7 1.420,	8 1.249,	9 1.271,	10 1.345,	11 1.139,	12 1.345
13 1.285,	14 1.362,	15 1.285,	16 1.360,	17 1.346,	18 1.346
19 1.186,	20 1.491,	21 1.173,	22 1.386,	23 1.346,	24 1.346

Revenue: Period 4

1 1.662,	2 1.662,	3 1.734,	4 1.664,	5 1.662,	6 1.664
7 1.569,	8 1.569,	9 1.404,	10 1.345,	11 1.431,	12 1.345
13 1.419,	14 1.362,	15 1.419,	16 1.360,	17 1.346,	18 1.346
19 1.490,	20 1.491,	21 1.474,	22 1.386,	23 1.346,	24 1.346

Total revenue over 4 periods discounted by 7%

1 4.364,	2 4.216,	3 4.909,	4 4.932,	5 4.425,	6 4.705
7 4.181,	8 4.041,	9 4.162,	10 4.178,	11 3.960,	12 4.062
13 4.454,	14 4.474,	15 4.454,	16 4.470,	17 4.501,	18 4.501
19 4.226,	20 4.476,	21 4.203,	22 4.309,	23 4.397,	24 4.397

In period 4, the difference between the best expansion path (3) and the worst (10 or 12) is now close to 30%. For the discounted total revenue over the four years, the difference between the best (4) and worst (11) expansion path is 24.5%.

6. Suggested Cures

As indicated by the examples presented, the regulatory regime for the transmission grid can have undesired effects on investment behavior. Given that an investment already has been carried out, in the case of traffic equilibria, marginal cost pricing can lead to improved overall system performance from grid modifications even when Braess' paradox occurs in user equilibrium (Pas and Principio [24]). In electricity networks there is no equivalent methodology, since electrons do not respond to marginal cost pricing. To alter line flows for a given set of injections, we would have to alter line impedances, i.e. the physical characteristics of the network.

The examples exhibited in section 4, that are similar to the classical Braess' paradox, show that having the merchandizing surplus as a determinant of grid revenue, may have undesirable effects regarding grid investments. Instead of investing in new capacity in order to relieve congestion, there are incentives to aggravate the constraints such that grid revenue increases. Such behavior is easy to detect in our simple examples, but exceedingly difficult to monitor and regulate in practice. The issue of how to encouraging beneficial investments and discouraging detrimental investments in this type of regime has been treated in the literature, for instance by Baldick and Kahn [1], Bushnell and Stoft [6] [7] [8] and Hogan [19]. As is shown by Bushnell and Stoft [6] [7], transmission congestion contracts (TCCs), where new contracts are allocated according to a feasibility rule, which helps internalizing the external effects of detrimental grid investments, can provide at least a partial solution. However, the results depend on TCCs matching the actual spot positions. Moreover, TCCs don't even exist as a part of the Nordic power market design.

In the Norwegian regulatory regime, merchandizing surplus does not in the same way provide investment incentives (or disincentives), because it has no direct effect on grid revenue. However, as is demonstrated by the examples of section 5, also the Norwegian regulation can induce "peculiar" investment behavior, as load growth and load reductions are not treated symmetrically, and are possible to manipulate by investment decisions. In this paper we have examined the sequencing of a given investment program. However, one should also be aware of the fact that changes in power flows can be induced by more subtle changes to the network than grid investments, for instance through the use of switches, shut-downs and changes in reactive power (Hogan [18], Kahn and Baldick [20]). This implies that a regulation relying on extensive monitoring, is extremely difficult in complex real world networks, with great information asymmetry between transmission owners / system operator and any other party.

In formula (2-2) the adjustment factor for load growth was chosen partly because it was considered an exogenously given parameter. We have demonstrated that it is not, and one solution could be to use a different factor for the annual adjustment of revenue caps, for instance customer growth as suggested by Grønli et al. [14]. This has already been carried out for low voltage distribution, where adjustments for new investments are accomplished through a factor based on new construction in the area of the distribution company, in addition to a factor based on increase in consumption on a national level. The problem with the latter as we see it, is that it is not necessarily well connected with investment cost in the area of a specific distribution company, so the correlation between the adjustment factor and the cost it is supposed to compensate for may be poor. For high voltage transmission, the regulation has been extended for one year, and the new adjustment factor will probably be based on consumption growth.

7. Conclusions

In this paper, we have seen that depending on the parameters of the problem considered (cost, demand, thermal capacity and admittance) a new line may be detrimental to social surplus and/or reduce transmitted energy. Thus, whether grid revenues are determined by the merchandizing surplus or by revenue caps like in the Norwegian system, the fact that the determinants of the revenues can be manipulated may lead to strange investment behavior. In general, some agents are better off while others lose due to such behavior.

The possibility of paradoxical effects and the incentives that they provide to different agents must clearly be taken into consideration both in the process of grid development and regulation. As such, the main point of this paper is that when assessing the incentive effects of a specific regulation, it is not enough to consider whether we are dealing with, for instance, a revenue regulation or a rate-of-return regulation, because the specific details of the regulation may be of major importance. This is particularly so in electricity networks and other networks operating under a decentralized control paradigm, since economic intuition to some extent falls short in this type of networks.

Finally, we have already commented on the extreme difficulty of dealing with investments in networks with adaptive routing. Bushnell and Stoft [8] point to the fact that the performance of an electric network depends on expected dispatch, which is influenced by future supply and demand conditions, which are constantly changing and subject to uncertainty. Thus, as market conditions change, so can the performance of the different network configurations considered. This is further complicated by typically long asset lifetimes and the lumpiness of the investment decisions, which sometimes makes it desirable to expand the network in a manner that is not immediately beneficial but will be in the long run. Ideally, we should compare different expansion *paths* rather than various fixed networks, as the investment problem is dynamic in nature.

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