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Congestion Pricing
and Network Expansion

Thomas-Olivier Nasser

Deregulation has transformed
such network industries as
gas, electricity, and
telecommunications. What
part does congestion pricing
play in the new environment
and, in particular, how does
congestion pricing affect
network expansion?

Summary findings

Over the past decade network industries (such as gas, electricity, and telecommunications) have undergone a dramatic transformation. Competition has been introduced in industries that had long been viewed as textbook examples of natural monopolies.

Production and transport have been unbundled to foster the introduction of competition: the capacity provider (the owner of the infrastructure) now often differs from the service provider. Chief among the challenges this raises for economists and policymakers: to design institutions that lead to "optimal" network expansion.

Different arrangements have been suggested, ranging from indicative planning to decentralization of investment decisions through congestion pricing. Two questions lie at the core of the debate: Is the infrastructure network still a natural monopoly? And what role should congestion pricing play in ensuring optimal network expansion?

Nasser shows that simple economic principles apply to the use of congestion pricing to induce network expansion:

• If network provision is competitive, congestion pricing leads to optimal investment.

• If network provision is monopolistic, congestion pricing leads to underinvestment.

He shows the model applying to power networks as well as to the Internet.

Policymakers must therefore assess whether network expansion is indeed competitive and design institutions that ease entry, or design an appropriate regulatory framework.

Congestion Pricing and Network Expansion

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A shadow price does not a market make. (Anonymous, quoted by Joskow [4])

1 Introduction

Over the last decade, network industries have undergone a dramatic transformation: competition has been introduced in industries that had long been viewed as text-book examples of natural monopolies, such as gas, electricity, and telecommunications. Production and transport have been unbundled to foster the introduction of competition: the capacity provider, i.e., the owner of the infrastructure, now often differs from the service provider. This situation raises new challenges for economists and policy makers. Chief among them is the design of institutions that will lead to "optimal" network expansion. Different arrangements have been suggested, ranging from indicative planning to decentralization of investment decisions through congestion pricing. Two questions lie at the core of the debate: is the infrastructure network still a natural monopoly? and what role could congestion pricing play? This article shows how simple economic theory sheds light on the argument, and informs the policy discussion.

In the early 80's, network industries in most countries were composed of vertically integrated utilities, subject to some form of governmental control. In the United Kingdom and in South America utilities were publicly owned. In the United States they were (for the most part) privately owned, and subject to regulatory oversight.

In many countries, today's industrial organization is dramatically different (see the survey by Klein [5]). First, utilities (or more exactly, their successor companies) are now privately owned. Second, and more importantly for this analysis, network industries are now competitive: production and transport have been unbundled, and vertical separation has been introduced. Usually, firms compete to provide service to customers, using the network infrastructure that often remains a monopoly. In the electricity industry, the transmission and distribution networks are sofar considered natural monopolies, while generation and retail sale to customers are competitive. In the United Kingdom, the monopolistic owner of the power transmission grid is not involved in generation nor retail sale of electricity, and the owner of the railway track does not offer passenger or freight service. In the telecommunications industry, the local network is (at least today) a natural monopoly[1], while long-distance telecommunications and value-added

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[1]MCI acknowledged in July 1997 a loss of $800 million in its efforts to penetrate local telecommunications

services are competitive. In the United States, the owner of the local telephone network does not provide all services transiting through these lines (internet access, long distance calls, etc.). In the gas industry, pipeline construction is competitive.

Introduction of competition has greatly reduced the need for centralized planning and bureaucratic decision making. However, residual economic regulation is necessary to foster competition in the competitive segments, and to insure efficient operation of the non-competitive segments. In many aspects, residual regulation is much more subtle and complex than the traditional utilities regulation, that treated the vertical chain that leads to the user as a black box, and was chiefly concerned with regulating the price of the output. Today, the regulator must open that black box, and design regulatory mechanisms that control one segment of the chain without compromising the others. For example, determination of access prices for the local loop in telecommunications has generated almost two decades of discussions (see the theoretical analysis of access pricing by Laffont and Tirole [8]).

One particular challenge is the design of an institutional framework that ensures optimal expansion of the network. Different arrangements have been proposed and/or implemented, that we can broadly classify into three categories: (1) planning by a government entity, (2) regulation of the network operator, and (3) decentralization of investment decisions supported by pricing of congestion on the network. In the electricity industry, Brazil has opted for the first solution, the United Kingdom for the second, and Argentina for the third.

This article applies general economic principles to determine conditions under which congestion pricing creates optimal investment incentives. The question is crucial for policy makers. If we find that congestion pricing yields optimal network expansion, additional regulation is not needed. On the other hand, if this is not the case, policy makers must set up a regulatory agency, and endow it with the appropriate tools.

The literature so far has been divided on this issue: while analysts agree that congestion pricing induces optimal usage of the existing network and generates revenue that can be used to finance network expansion, opposite views are held on the incentives congestion pricing creates for decentralized network expansion.

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markets. This loss (and the subsequent judicial ruling that the FCC has no mandate to impose federal competition rules to local telephone companies) suggest that, contrary to the vision of the Telecommunications Act of 1996, local telecommunications remain a natural monopoly.

All agree that inclusion of a congestion charge in the price forces users to face the congestion externality they are imposing on others. This modifies their behavior, hence increases the use of the existing capacity. Pricing for road congestion is the simplest example[2]. If drivers are charged more to use the network during peak-hour, they modify their departure time, or carpool. Hence, usage of the existing highway is more evenly spread during the day and capacity expansion is less urgent.

As for network expansion, the proponents' argument goes as follows: congestion pricing signals the value of additional capacity, hence creates correct incentives. MacKie-Mason and Varian [10] study a simple model of congestion for a telecommunications network, and conclude that: "optimal congestion pricing plays two roles - it efficiently rations access to the network in times of congestion, and it sends the correct signals about capacity expansion". In the power industry, Hogan [3] advocates the use of Transmission Congestion Contracts to signal the cost of congestion, hence the value of additional capacity.

The opponents' argument relies on the following: suppose the network owner's revenues are based on congestion. Then, his profit maximization leads to an increase rather than a decrease of the congestion on the network. This view has been supported by Bushnell and Stoft [2] in the case of electricity.

This article argues that the simplest principle of economics, embodied in the opening quote, applies to these seemingly complex network problems: *competition and not prices induces optimal capacity expansion.* Congestion pricing does provide correct economic signals for network expansion. Without congestion pricing, economic information needed for expansion is not produced, hence optimal expansion is unlikely to occur. However, creation of economic signals constitute only part of the story. If competition to provide additional network capacity is strong, congestion pricing does lead to optimal network expansion. If competition is weak, and in the extreme case, if network provision is monopolistic, congestion pricing leads to suboptimal expansion of the network.

Our argument proceeds as follows. First, we show that the socially optimal network expansion is such that the marginal cost of capacity equals its marginal social value (i.e., the marginal value of congestion reduction due to a marginal increase in capacity).

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[2] However, Singapore constitutes the only documented example of road congestion pricing.

Second, as pointed out by Hogan [3] and MacKie-Mason and Varian [10], the revenue from congestion pricing measures the value of additional capacity. Under general assumptions, we prove that the congestion revenue is precisely equal to the network capacity times its marginal social value.

Consider then a network owner who receives this congestion revenue. His optimal capacity choice requires that the marginal revenue of capacity equals its marginal cost. If he builds an additional unit of capacity, his revenue increases by the marginal value (on the marginal unit), while simultaneously the marginal value is lowered (on all inframarginal units). He then follows a familiar inverse elasticity rule and expands the network less than is socially optimal. Capacity provision is formally equivalent to Cournot competition[3].

On the other hand, if competition for network capacity is strong enough, providers will compete up to the point where the marginal value of capacity equals its marginal cost. Congestion pricing and effective open-entry lead to optimal expansion.

We prove that this framework encompasses and reconciles the apparently conflicting congestion pricing models presented by Bushnell and Stoft [2] for power networks, and MacKie-Mason and Varian [10] for the Internet.

The rule for policy makers is therefore: (1) use congestion pricing to send users signals about the cost of their usage, and (2) if network expansion is not competitive, regulate the network owners to induce them to expand the network.

The article is organized as follows. Section 2 presents a model of congestion for power systems. Section 3 presents a model of congestion for the internet, proposed by MacKie-Mason and Varian, and shows that both models are in fact equivalent. Section 4 discusses policy issues. Section 5 concludes.

2   Congestion on a Power Network

This Section presents a first model of congestion pricing. It follows closely Nasser [11], that builds on the seminal treatment presented by Schweppe et al. [14]. In this model, congestion creates a hard constraint. One segment of the network has a given capacity, that cannot be exceeded. This representation is appropriate for transmission capacity constraints on power

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[3] Capacity provision is probably one of the most realistic examples of Cournot competition.

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networks (see Schweppe et al. [14] for more details).

We present in this Section a non-mathematical treatment of the problem. For the interested reader, supporting equations are presented in the Appendix.

2.1 A Simple Network

Consider the two-node power network represented on Figure 1. Electricity demand is located in the West node, while generation is present at both the West and East nodes. q_W and q_E are the power generations at the West and East nodes respectively, and d_E is the power demand at the East node. For simplicity, we assume d_E is constant, and without loss of generality, we normalize $d_E = 1$. A transmission line with capacity K links both regions.

$g_W(q_W)$ and $g_E(q_E)$ are the marginal costs of power generation at the West and East nodes respectively. We assume that generation at the West node is always cheaper (at the margin) than at the East node. For example, hydro-power is generated at the West node, while thermal power is produced at the East node:

$$g_W(q_W) < g_E(q_E), \forall(q_W, q_E)$$

Finally, we assume that the DC Load approximation holds, and that transmission losses are negligible.

2.2 Optimal Usage

The market is organized by a central market-maker (often called a "smart market"). Generators bid the price at which they are willing to supply power to the market, users the price at which they are willing to buy power[4]. The market-maker then runs the computer algorithm that maximizes the surplus from consumption net of generation costs, subject to the market clearing and the transmission constraint conditions.

We assume perfect competition in consumption and generation: consumers truthfully report their demand function and generators their supply function, at no cost for the market-maker[5].

Suppose first that the transmission capacity K exceeds demand at the East node: $K \geq 1$. The optimal dispatch calls for the cheaper West generators to meet all demand: $q_W = d_E = 1$,

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[4]More generally, participants in the market bid a price/quantity schedule: supply function for generators, demand function for generators.

[5]"Gaming" from generators is examined in Nasser [11], Chapters 3 and 4.

and $q_E = 0$.

Suppose now that the transmission capacity is lower than demand at the East Node: $K < 1$. The optimal dispatch, represented in Figure 2, calls for the cheaper generators at the West node to generate only $q_W = K$, while the more expensive generators in the East node generate the residual quantity $q_E = 1 - K$.

Congestion in the transmission network implies that more expensive generators must be turned on.

2.3 Marginal Value of Transmission Capacities

To determine the marginal value of transmission capacity, consider a marginal increase of one unit in transmission capacity. This enables the smart-market to substitute one unit of cheap power generated at the West node for one unit of expensive power generated at the East node, which leads to:

Result 1 *The marginal value of transmission capacity is the difference between the marginal costs of generation at the extremities of the transmission line.*

Furthermore, since generation costs are increasing, the marginal value of transmission capacity is decreasing when capacity is increasing, as illustrated on Figure 3: an increase in capacity of the congested facility increases the net surplus, at a decreasing rate. This mathematical result has a strong economic interpretation: prices reflect scarcity. As transmission capacity becomes more abundant, its marginal value decreases. In particular, the marginal value of capacity on a uncongested transmission line is equal to zero.

Result 1 allows us to characterize the optimal transmission capacity K^*. An increase in transmission capacity allows the dispatcher to substitute cheap for expensive power. On the other hand, it is costly:

Result 2 *At the optimal capacity K^*, the marginal value of capacity equals its marginal cost.*

Result 2 implies that, if the marginal cost of transmission capacity is positive, the line must be congested a fraction of the time at the optimum. If a transmission line is *never* congested, it is over-sized.

Residual congestion at the optimum appears consistent with engineering design standards. In Brazil, transmission lines are dimensioned to be congested 5% of the time. However, Result 2 suggests that the optimal congestion level is not arbitrarily set to 5%, but depends on the cost of congestion, i.e., ultimately the marginal cost of generation, as well as users' willingness to pay for power.

2.4 Congestion Pricing

We now turn to electricity and congestion pricing. p_W is the price of power at the West node, i.e. the price at which the smart-market purchases power from the West generators. p_E is the price of power at the East node, i.e. the price at which the smart-market purchases power from the East generators, and sells it to the consumers. If the network is not congested, the price of power at the East and West nodes is simply the marginal cost of power generated at the West node: $p_E = p_W = g(1)$.

Suppose now that the network is congested, and that congestion is not priced: the smart-market buys power at marginal cost from the West and East generators, and sells it at the average marginal cost of generating power and breaks even:

$$\bar{p}_E.1 = K g_W + (1 - K) g_E$$

Suppose now that congestion is priced. Since the transmission line is congested, a marginal electricity demand at the East Node can be met only by using expensive power generated at the East node: the optimal price of power at the East node is $p_E = g_E(q_E)$.

Users at the East node pay a price higher than the average marginal cost of generation: $p_E > \bar{p}_E$, to account for their contribution to congestion.

Furthermore, we can verify that:

$$p_E = \bar{p}_E + (g_E - g_W)K$$

The optimal price of power at the East node is the average marginal cost of power generation plus a congestion charge, equal to the transmission capacity times its marginal value[6]:

Result 3 *Optimal pricing of electricity implies a transmission charge equal to the transmission capacity times its marginal value: the congestion rent.*

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[6] This result is a duality equation, and is extremely general.

The transmission charge varies with the congestion level.

Suppose that a profit-maximizing private firm owns the transmission lines, and receives the transmission capacity times its marginal value. We prove in the Appendix (Proposition 1) that:

Result 4 *The profit-maximizing transmission capacity is lower than the socially optimal one.*

This result has an intuitive economic interpretation, independent of the network context: the producer of a good knows that, if he produces one more unit of the good, he earns the price of the good on that last unit, but, if he cannot price-discriminate among consumers, he also *reduces* the price he obtains on all inframarginal units. Congestion pricing in power systems does not induce optimal expansion. Competition to provide transmission, or residual regulation of transmission companies are needed.

3 Congestion on the Internet

This Section presents the model of congestion pricing developed by MacKie-Mason and Varian [10]. Here, congestion does not create a hard constraint, rather it produces delays. However, as shown below, the economic intuition is unchanged.

3.1 Notation

We consider the simple model of the Internet presented on Figure 4: two users are connected to the network. q_1 and q_2 are the network usages for users 1 and 2 respectively (e.g., number of bits transmitted). $Q = q_1 + q_2$ is the total network usage, K is the network capacity, and $Y = Q/K$ is the network utilization.

Congestion creates delay D on the network. We suppose that D is an increasing function of the network utilization Y : delay D increases when the usage Q increases, and decreases when capacity K increases.

3.2 Marginal Value of Capacity

Since an increase in network capacity reduces delay, we immediately have:

Result 5 *The marginal value of network capacity equals the marginal delay reduction (implied by capacity increase). The optimal network capacity is such that the marginal cost of capacity*

equals the marginal delay reduction.

This result is similar to Results 1 and 2 for power systems. We show in the Appendix B that the marginal value of capacity decreases when capacity increases.

3.3 Optimal Usage and Congestion Pricing

Suppose first that users pay only a fixed-fee, independent of their network use. We show in the Appendix B that users then consume up to the point where the marginal utility from consumption equals zero: users consume almost an infinite amount.

This result explains the misfortune encountered by America On Line when it introduced a new pricing plan: unlimited access to the service for $19.95 per month. Many users stayed too long on-line, and the network became awfully congested.

Suppose now that the network operator can compute the marginal delay created by usage, and that users pay a congestion charge precisely equal to that marginal delay. McKie-Mason and Varian [10] propose a scheme that links priority and congestion pricing: each information packet contains a header, into which a priority code can be coded. Each router would then drop or delay lower priority packets at congested periods and this would then be the basis for charging. Higher priority packets would pay for this prioritizing on a statistically sampled basis. We then have:

Result 6 *If users are charged their marginal contribution to congestion, they consume optimally.*

This result is the application to the Internet of an extremely general property, that has long been known to economists.[7]

Suppose the network operator collects these charges. We have:

Result 7 *The revenue from congestion pricing equals the capacity times its marginal value.*

We now examine network expansion:

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[7] At least since Pigou formalized issues of externalities in 1920.

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Result 8 *If network operators compete perfectly, they choose: (1) the optimal network capacity, and (2) the optimal congestion charge. If the network operator is a monopoly, he chooses a network capacity lower than the optimum (Propositions 2 and 3 in Appendix B).*

Thus, even though they appear different, congestion on the internet and on a power network involve the same fundamental economic principle: the value of a good increases with its scarcity.

In fact both models of congestion are equivalent. Consider for example congestion at an airport. Delay experienced by travellers increases with the number of planes. It seems that the delay model of congestion is appropriate. However, in practice air traffic controllers set firm limits on the number of take-offs per minute, etc. The fixed capacity model of congestion then seems correct.

4 Policy Issues

From the previous discussion, we propose the following rule for policy makers: (1) use congestion pricing to send users signals about the true cost of their usage, and (2) if the network expansion is not competitive, regulate the network owners to induce them to expand the network. This Section discusses implementation issues reduced to smart markets, congestion pricing, competition, and regulation in network provision.

4.1 Smart Markets

Smart markets are easier to set up when the network has historically been centrally controlled: in Chile, the United Kingdom, Norway, Argentina, Colombia, New Zealand, the State of Victoria in Australia, Pools coordinate electricity trades. In Norway, a smart market to allocate rights to railway track is under examination.

In other instances, creation of a smart market is more difficult. The restructuring of the power industry in California has given rise to a lengthy and vigorous debate about the benefits and costs of a smart market (Joskow [4] provides an insightful account of the discussion). Some feared that the market-maker would abuse his monopoly power (Wu et al. [15] and Oren et al. [12]). For example, if the market-maker also owns the network and receives the congestion rent, he has incentives to distort the dispatch to maximize his revenues. For many power systems,

the dispatch room is physically located within the transmission company, which fuels the fear that the network owner influences the market-maker.

These concerns do not undermine the economic benefits of a smart market. They simply imply that important institutional issues must be carefully addressed: coordination between the market-maker and the network owner, procedures of appeal of the market-maker's decisions, mechanisms to modify the market-maker's procedures, etc. The market-maker must be independent from the network owner. The computer program that determines the optimal dispatch must be available to, and auditable by, all market participants. Proper incentives and governance structure must be put in place. In particular, the market maker's remuneration should be unrelated to the dispatch[8].

In the case of telecommunications networks, the dispatch function is decentralized to multiple routers. As suggested by McKie-Mason and Varian[10], there is no longer a single "visible hand", rather a large number of hierachically organized invisible hands[9].

In the airlines industry, dispatch is also decentralized to each airport, with coordination through conventions and rules.

4.2   Congestion Pricing

Marginal congestion pricing has users pay for the marginal externalities they are creating. The competitive equilibrium then decentralizes the social optimum, and induces optimal usage of the existing capacity. The smart market is exactly the Walrasian auctioneer. This result is undisputed, and hardly new.

For most situations encountered by economists, the marginal externality created by each user is hard to compute. In the particular case of power systems, however, the DC Load approximation provides a good approximation of this marginal externality. Furthermore, the value of the marginal externality is a by-product of the optimal dispatch: a power system that uses an optimal dispatch algorithm can therefore easily implement congestion pricing.

Decentralized congestion pricing is not always as easy to implement. This requires more sophisticated trading mechanisms, with interruptible service, etc. Experience with the Internet

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[8] Of course, the remuneration can (and should) depend on the quality of the dispatch, for example the number of dispatch errors, etc.

[9] Recent optimal dispatch algorithms for power systems also use a hierachical control architecture.

suggests that such schemes are feasible: corporate users are willing to pay a premium for increased reliability. Peak versus off-peak pricing is obviously the simplest scheme.

Congestion pricing may be politically difficult to implement, and unpleasant for customers. It was decided in 1990 that the bulk price of electricity would be uniform in the United Kingdom. Retail price, however, varied to account for distribution charges. Since then, transmission charges have been progressively differentiated across regions to account for congestion and losses, and further differentiation is currently under examination. The electricity regulator, Stephen Littlechild reports ([9], pg 3) letters of protests from Members of Parliament whose districts are adversely affected by the differentiation.

In the US, a major telephone carrier (AT&T) now markets uniform rates, to replace the peak versus off-peak pricing. This suggests over-capacity on the long-distance network, but may also reflect marketing considerations: users respond favorably when offered (for a premium) not to worry about the timing of their call.

There is currently no formal congestion pricing at airports. Airlines charge their customers additional flight-time to account for delays in take-off and landing due to congestion on the runway or at the gates. As air-traffic grows, and with constant airport capacity, formal congestion pricing will become necessary. Queuing theory and probabilistic modelling have recently allowed researchers to compute the marginal contribution to congestion created by an airplane delay. Pricing may soon follow.

4.3 Competitive Network Provision

The analysis in Sections 2 and 3 shows that congestion pricing (even optimal congestion pricing) does not imply optimal network capacity expansion. If network provision is a monopoly, congestion pricing creates incentives for under-investment in capacity.

The empirical question is therefore: for which industries do we believe that network provision can be made competitive? When do the revenues from congestion pricing exceed the cost of capacity expansion, so that, if the existing network owner fails to expand the network, another company can profitably increase capacity?

One can safely predict that, in the long-run, technological advances most likely will make competitive provision feasible for all networks. In the short-run, however, policy makers do

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not have the luxury of experimentation: they must determine the scope of regulation while restructuring proceeds. We review below the evidence for different systems.

4.3.1 Competition in Power Transmission

Common wisdom suggests that the power transmission and distribution networks are natural monopolies. Perez-Arriaga et al. [13] document that, for many existing power networks, the congestion rent represent roughly 30% of the cost of the transmission grid. This indicates that, while congestion rents may contribute to finance network expansion (as in Argentina), they cannot constitute the only source of revenue for the network operator.

However, we present a simple calculation that suggests that congestion rents may finance new transmission investments. Consider again the simple two-node power network presented in Figure 1. Denote $\Delta p = g_E - g_W$ the difference in power prices, measured in $/MWh$, and K the capacity of the transmission line, measured in MW. As shown in Section 2, the hourly congestion rent is $R = K \cdot \Delta p$.

For this simple numerical example, we assume that Δp is: (1) independent of K (constant marginal costs of generation), and (2) constant over time[10]. Denote h the numbers of hours a year that the constraint is binding, and δ the annual discount rate. The net present value of the congestion rent is then: $\tilde{R} = \frac{h \cdot K \cdot \Delta p}{1 - \delta}$. Suppose that the cost of transmission is: $C(K) = cK$.

Consider now a potential investor[11]. The congestion rents finance transmission investment if and only if:

$$h \geq \frac{(1 - \delta)c}{\Delta p}$$

Denote H the number of hours in a year, and $n = h/H$ the minimum fraction of the time that the line must be congested for the investment to be profitable, that we call the congestion fraction. We present in Tables 1, 2, and 3 values of the congestion fraction for different lengths of line.

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[10] If the later condition is not met, we replace Δp by its expectation at the date of the investment.

[11] Denote K_0 the existing capacity, and $\bar{K}$ the maximum capacity, i.e, the demand at East. Our simplifying assumptions imply the following knife-edge characterization of the socially optimal capacity:

$$K^* = \begin{cases} K_0 & if \quad c > \frac{h \cdot \Delta p}{1 - \delta} \\ K_0 \leq K \leq \bar{K} & if \quad c = \frac{h \cdot \Delta p}{1 - \delta} \\ \bar{K} & if \quad c < \frac{h \cdot \Delta p}{1 - \delta} \end{cases}$$

	$c = 200$	$c = 500$	$c = 1,000$
$\Delta p = 10$	4%	10%	21%
$\Delta p = 40$	1%	3%	5%
$\Delta p = 100$	0.42%	1%	2%
$\Delta p = 200$	0.21%	1%	1%

Table 1: Congestion Fraction for a 200 km line

	$c = 200$	$c = 500$	$c = 1,000$
$\Delta p = 10$	10%	26%	52%
$\Delta p = 40$	3%	6%	13%
$\Delta p = 100$	1%	3%	5%
$\Delta p = 200$	1%	1%	3%

Table 2: Congestion Fraction for a 500 km line

We consider three values of average cost for transmission lines. The lower value is \$200 per MW.km. This corresponds to the value reported by the Brazilian electricity company Electrobras for a 500 kV line. The intermediate value is \$500 per MW.km. This is slightly above the average value reported by NGC, the transmission company in the United Kingdom (\$400 per MW.km). Finally, the upper value is \$1,000 per MW.km, reported by New England Power Service in the United States.

We also consider four values of Δp. The lowest value is $\Delta p = 10$. The highest value $\Delta p = 200$ is larger than the difference between the highest bids in the United Kingdom Pool (\$190 per MWh) and the average Pool price (\$40 per MWh). The discount rate is $\delta = \frac{1}{1+r}$, where r is the interest, set at $r = 10\%$. The results are robust to sensitivity on the interest rate.

Table 1 shows that congestion less than 5% of the time is sufficient for a short line (200 km) to be financially viable for $\Delta p \geq 40$, for all cost scenarios. Congestion less than 6% of the time is sufficient for an intermediate line (500 km), except for the high cost (Table 2). Large

	$c = 200$	$c = 500$	$c = 1,000$
$\Delta p = 10$	21%	52%	104%
$\Delta p = 40$	5%	13%	26%
$\Delta p = 100$	2%	5%	10%
$\Delta p = 200$	1%	3%	5%

Table 3: Congestion Fraction for a 1,000 km line

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price differentials are needed to make a long line financially viable with low congestion (Table 3).

It would be premature to infer from this simplistic calculation that private investment is going to flow into electricity transmission. Policy makers may be concerned by the cost of coordination of multiple transmission line owners. In particular, our analysis ignores reliability issues, that are crucial for transmission networks, as well as externalities between transmission lines, which imply that oligopolistic competition in generation may lead to higher congestion than a monopoly (see the analysis presented in Nasser [11], Chapter 5).

The calculation simply suggests that the conventional wisdom might be amended, and that short transmission lines, remunerated by congestion rents, might well be attractive for private investors.

4.3.2 Competition in Telecommunications Networks

There seems to be a consensus that long-distance telecommunication lines and wireless communications are competitive, which indicates that there is no need to regulate network expansion. Of course, interconnection agreements, numbering and radiofrequency allocation, etc. must be regulated.

However, competing telecommunications networks exert externalities between each other: users connected to network A will desire to communicate with users connected to network B. This crucial fact, omitted in the analysis presented by McKie-Mason and Varian [10] may induce suboptimal network expansion, as shown by Laffont, Rey, and Tirole [6] and [7].

4.4 Airline Industry

Even if congestion pricing was to provide a value for expansion needs, it is not clear that airports can easily expand their capacity. Environmental considerations appear to limit addition of new runways, let alone construction of new airports. However, advanced-control technology may contribute to increase capacity without physically expanding the airport.

4.5 Regulated Network Provision

Regulation of a monopoly transmission company is not an easy task. The regulation contract must induce the transmission company to: (1) minimize the cost of transmission, while passing

some savings through to the users (the rent extraction/cost minimization trade-off), and (2) choose the socially optimal transmission capacity. In the United Kingdom, the second objective has proved difficult to achieve (see Nasser [11], Chapter 6, for an analysis and possible solution).

In many instances, the network is historically owned by different corporations. For example, in the US, power transmission lines are owned by different vertically integrated utilities; in Brazil, the transmission network is jointly owned by the Federal Government and the States. Regulation of multiple companies presents its own set of challenges. (see Auriol and Laffont [1].)

5   Conclusion

This article has shown that simple economic principles apply to the use of congestion pricing to induce network expansion: if network provision is competitive, congestion pricing leads to optimal investment; if network provision is monopolistic, under-investment arises. The model is shown to apply to abstract power networks as well as the internet. The intuition extends to other congested networks, such as gas, roads, rail, airports, etc. Policy makers must therefore: (1) assess whether network expansion is indeed competitive, and (2) design institutions that ease entry, or design an appropriate regulatory framework.

Further research should aim to determine industries for which network provision is potentially competitive. This involves: (1) theoretical analysis of congestion pricing, and determination of the congestion rents, and (2) empirical analysis of the congestion rents, and comparison with the cost of additional capacity. Empirical analysis of the users' willingness-to-pay for congestion reduction will also shed light on the debate.

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APPENDIX

A Congestion on a Power Network

A.1 Notation

Consider a N-node network. At each node, a non-storable[12] good is produced and/or consumed. q_n^s and q_n^d are respectively the quantities generated and consumed at node n. $q_n = q_n^s - q_n^d$ is the net injection into the network: the difference between local generation and local consumption at node n. $C_n(q_n^s)$, and $CS_n(q_n^d)$ are the cost of generation and the gross surplus from consumption at node n. $S_n(q_n^s, q_n^d) = CS_n(q_n^d) - C_n(q_n^s)$ is the net surplus at node n. With $C_n(.)$ convex and $CS_n(.)$ concave, $S_n(.,.)$ is concave. $\mathbf{q} \in \mathbb{R}^N$ is the vector of net injections into the network.

Since the good is non storable, the market clearing implies that: $\sum_{n=1}^N q_n^s = \sum_{n=1}^N q_n^d$.

Suppose now that the existence of a bottleneck on the network. Congestion depends only on net injections into the network, i.e., on the vector $\mathbf{q} \in \mathbb{R}^N$. Precisely, we denote K the capacity on one segment of the network, and we assume that the flow on that segment can be expressed as a function $Z = g(\mathbf{q})$, where $g(.)$ is linear. Denote $Y = \frac{Z}{K}$ the total utilization of the segment. The network is congested if and only if $Y = 1$.

For example, consider a power network. Under the DC Load approximation, we can express power flows on each line as a linear function of the net injections. If K is the capacity on line 1, for example, we have: $Z = g(\mathbf{q}) = \sum_{n=1}^{N-1} H_{1n} q_n$, where $\mathbf{H}$ is the transfer admittance matrix[13].

A.2 Optimal Usage and Congestion Pricing

We suppose the market is organized by a "smart market": users report $CS_n(.)$ and $C_n(.)$ to a benevolent network dispatcher. He then maximizes the surplus from consumption, subject to the market clearing and network constraints. We assume that users truthfully report their surplus, at no cost for the dispatcher.

$\mathcal{V}(K)$ is the net surplus at the optimal dispatch:

$$\mathcal{V}(K) = \begin{cases} \max_{q_n^s, q_n^s} \sum_{n=1}^N S_n(q_n^s, q_n^s) \\ st: \begin{cases} \sum_{n=1}^N q_n = 0 \\ g(\mathbf{q}) \leq K \end{cases} \end{cases}$$

Denote μ and η the Lagrange multipliers on the market clearing and network constraints. The Lagragian of the program is:

$$\mathcal{L}(\mathbf{q}, \mu, \eta) = \sum_{n=1}^N S_n(q_n^s, q_n^s) + \mu \sum_{n=1}^N q_n + \eta(K - g(\mathbf{q}))$$

Under our assumptions, the program is concave, and the first-order conditions determine the unique optimal production/consumption plan $\mathbf{q}^* \in \mathbb{R}^N$:

$$\begin{cases} \frac{\partial CS_n}{\partial q_n^s}(q_n^{s*}) - \mu^* + \eta^* \frac{\partial g(\mathbf{q}^*)}{\partial q_n} = 0 \\ -\frac{\partial C_n}{\partial q_n^s}(q_n^{d*}) + \mu^* - \eta^* \frac{\partial g(\mathbf{q}^*)}{\partial q_n} = 0 \end{cases}$$

---

[12] The argument is not modified if the good is storable.

[13] The interested reader is refered to Schweppe et al. [14] and Nasser [11] for details .

Schweppe et al. [14] propose an intuitive interpretation of the optimal dispatch $\mathbf{q}^* \in \mathbb{R}^N$. They introduce the nodal prices ρ_n, the marginal cost of a net injection at node n: the value of the marginal unit μ, minus the marginal contribution to the congestion $\frac{\partial g}{\partial q_n}$, valued at the shadow price of the congestion constraint η:

$$\rho_n = \mu - \eta \frac{\partial g(\mathbf{q})}{\partial q_n}$$

Schweppe et al. [14] show that the first-order conditions are:

$$\frac{\partial CS_n(q_n^{d*})}{\partial q_n^d} = \frac{\partial C_n(q_n^{d*})}{\partial q_n^s} = \rho_n^* \tag{1}$$

The optimal dispatch is such that, at node n, the marginal surplus is equal to the marginal cost and to the nodal price.

Equation (1) lends itself to the following interpretation: the dispatcher sets the price system: $p_n = \rho_n$ at each node. For example, a net exporter into the network $(q_n \geq 0)$ is paid μ, the cost of the most expensive unit produced, minus $\eta \frac{\partial g(\mathbf{q})}{\partial q_n}$, its marginal contribution to congestion, valued at the shadow price of the congestion constraint. In other words, users facing the nodal prices fully internalize the cost of the congestion externality they are creating.

The First-Welfare Theorem in the presence of externalities guarantees that users facing such a price system choose the socially optimal dispatch $\mathbf{q}^* \in \mathbb{R}^N$.

A.3 Optimal Capacity Expansion

We now turn to the incentives for capacity expansion generated by congestion pricing. With a slight abuse of notation, we denote $\eta(K)$ the shadow price of the congestion constraint at the optimal dispatch. We immediately establish the following result:

Theorem 1 *1. $\mathcal{V}(K)$ is a concave function of K.*

2. The shadow price of the transmission constraint is equal to the marginal value of transmission capacity (Result 1 in Section 2):

$$\frac{d\mathcal{V}(K)}{dK} = \eta(K)$$

Proof. Consider two values K_1 and K_2, and $0 \leq \alpha \leq 1$. By definition, we have:

$$\mathcal{V}(\alpha K_1 + (1-\alpha)K_2) = \left\{ \begin{array}{c} \max_{q_n^s, q_n^s} \sum_{n=1}^N S_n(q_n^s, q_n^s) \\ st : \left\{ \begin{array}{c} \sum_{n=1}^N q_n = 0 \\ g(\mathbf{q}) \leq \alpha K_1 + (1-\alpha)K_2 \end{array} \right. \end{array} \right.$$

Denote $\mathbf{q}^*(K)$ the optimal dispatch for capacity K. We first show that $\alpha \mathbf{q}^*(K_1) + (1-\alpha)\mathbf{q}^*(K_2)$ is feasible. Since $g(.)$ is linear:

$$g[\alpha \mathbf{q}^*(K_1) + (1-\alpha)\mathbf{q}^*(K_2)] = \alpha g[\mathbf{q}^*(K_1)] + (1-\alpha)g[\mathbf{q}^*(K_2)]$$

then, with $g[\mathbf{q}^*(K_1)] \leq K_1$ and $g[\mathbf{q}^*(K_2)] \leq K_2$, we have:

$$g[\alpha \mathbf{q}^*(K_1) + (1-\alpha)\mathbf{q}^*(K_2)] \leq \alpha K_1 + (1-\alpha)K_2$$

Then, by concavity of $f(.)$:

$$f[\alpha \mathbf{q}^*(K_1) + (1-\alpha)\mathbf{q}^*(K_2)] \geq \alpha f[\mathbf{q}^*(K_1)] + (1-\alpha)f[\mathbf{q}^*(K_2)] = \alpha \mathcal{V}(K_1) + (1-\alpha)\mathcal{V}(K_2)$$

Finally, since:

$$f[\mathbf{q}^*(\alpha K_1 + (1-\alpha)K_2)] \geq f[\alpha \mathbf{q}^*(K_1) + (1-\alpha)\mathbf{q}^*(K_2)]$$

we have:

$$\mathcal{V}(\alpha K_1 + (1-\alpha)K_2) \geq \alpha \mathcal{V}(K_1) + (1-\alpha)\mathcal{V}(K_2)$$

which establishes the concavity of $\mathcal{V}(.)$.

To establish the second result, we apply the envelope theorem:

$$\frac{d\mathcal{V}}{dK} = \frac{d\mathcal{L}}{dK} = \eta(K)$$

■

We immediately obtain the following:

Corollary 1 *Suppose that the network is congested, i.e., $Y = 1$. The shadow price η is a decreasing function of capacity K:*

$$\frac{d\eta(K)}{dK} \leq 0$$

Proof. The proof follows immediately from the previous theorem. Concavity of $\mathcal{V}(K)$ implies:

$$\frac{d^2\mathcal{V}(K)}{dK^2} = \frac{d\eta(K)}{dK} \leq 0$$

■

The previous theorem carries another important implication. Denote $C(K)$ the cost of capacity K. As usual, we suppose that $C(.)$ is increasing and convex. We then have:

Corollary 2 Optimal Capacity Expansion. *At the optimal capacity K^*, the marginal value of capacity equals its marginal cost (Result 2 in Section 2):*

$$\eta(K^*) = C'(K^*) \tag{2}$$

Proof. Denote $W(K) = \mathcal{V}(K) - C(K)$ the net surplus from capacity K. The optimal capacity maximizes $W(K)$. Since $\mathcal{V}(.)$ is concave and $C(.)$ is convex, $W(.)$ is concave. The first-order condition then characterizes the maximum:

$$\frac{dW}{dK} = 0 = \eta(K) - C'(K)$$

■

The result is intuitive: a marginal increase in capacity raises the surplus by $\eta(K)$. At the optimum, this increase is equal to the marginal cost of additional capacity.

A.4 Revenues from Congestion Pricing and Under-investment

We define the congestion rent:

Definition 1 *The congestion rent is the capacity times its marginal social value:*

$$R(K) = K \times \eta(K)$$

Suppose now that we are using congestion as a signal for investment. We could think of two ways: (1) pay the network owner the congestion rent, or (2) leave all the revenue from congestion pricing to the owner. With our hypotheses, it turns out that both approaches are equivalent:

Theorem 2 *The revenues from congestion pricing equal the congestion rent (Result 3 in Section 2):*

$$-\sum_{n=1}^{N} q_n^* \rho_n^* = R(K)$$

Proof. From equation (1), we have:

$$-\sum_{n=1}^{N} q_n^* \rho_n^* = -\mu \sum_{n=1}^{N} q_n^* + \eta \sum_{n=1}^{N} q_n^* \frac{\partial g(\mathbf{q}^*)}{\partial q_n}$$

Using the market clearing condition: $\sum_{n=1}^{N} q_n^* = 0$ and the linearity of $g(.)$: $\sum_{n=1}^{N} q_n^* \frac{\partial g(\mathbf{q}^*)}{\partial q_n} = g(\mathbf{q}^*)$, we have:

$$-\sum_{n=1}^{N} q_n^* \rho_n^* = -\mu \times 0 + \eta \times g(\mathbf{q}^*) = \eta \times K = R(K)$$

■

We are now in position to characterize the network owner's choice of capacity:

Proposition 1 *Leaving the congestion rent to the network owner induces under-investment. He chooses the monopoly capacity K^M that satisfies:*

$$\eta(K^M) + K^M \eta'(K^M) = C'(K^M) \tag{3}$$

Proof. The network owner chooses K to maximize its profit:

$$\pi(K) = \eta(K) \times K - C(K)$$

The second-order condition is:

$$\pi''(K) = K\eta''(K) + 2\eta'(K) - C''(K)$$

If $K\eta''(K) + 2\eta'(K) \leq 0$, which happens if $\eta''(K)$ is small, the program is concave. The first-order condition is exactly (3). ■

Proposition 1 formalizes Result 4.

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B Congestion on the Internet

B.1 Notation

Consider a N-node network. A user has utility $S_n(q_n) - D$, where q_n is the number of packets sent by user n and D is the total delay experienced by the user. The production cost of packets is included into $S_n(.)$. We suppose $S_n(.)$ is concave. Denote K the capacity of the network, $Q = \sum_{n=1}^{N} q_n$ the total usage of the network, and $Y = \frac{Q}{K}$ the total utilization of the network. We suppose that $D = D(Y)$, where $D(.)$ is an increasing function.

B.2 Usage Without Congestion Pricing

We assume users do not internalize the impact of their own usage on the delay they experience. Suppose first that there is no congestion pricing. Each user solves:

$$\max_{q_n} S_n(q_n) - D$$

which yields the first-order condition:

$$S_n'(q_n) = 0$$

Since there is no price for consumption, users consume up to the point where their marginal utility is equal to zero.

B.3 Optimal Usage and Congestion Pricing

Consider now the optimal usage of the network. A benevolent dispatcher chooses the consumption plan $\mathbf{q}^* \in \mathbb{R}^N$ to maximize the sum of all users utilities:

$$\mathcal{V}(K) = \max_{\mathbf{q} \in \mathbb{R}^N} \{ \sum_{n=1}^{N} S_n(q_n) - nD(\frac{Q}{K}) \}$$

The first-order conditions yield:

$$S_n'(q_n^*) = \frac{n}{K} D'(\frac{Q^*}{K}) \tag{4}$$

Equations (1) and (4) are formally identical: the optimal dispatch $\mathbf{q}^* \in \mathbb{R}^N$ is such that the marginal utility equals the marginal cost of congestion for each user.

As in the previous case, we can decentralize the optimal dispatch through prices. We set a price per packet equal to the marginal externality created:

$$p = \frac{d}{dq_n}(nD(\frac{Q}{K})) = \frac{n}{K} D'(Y)$$

Each user then maximizes:

$$\max_{q_n} \{ S_n(q_n) - \frac{n}{K} D'(Y) q_n \}$$

Again assuming that users do not internalize their own contribution to congestion $\frac{\partial Y}{\partial q_n}$, the first-order conditions are:

$$S_n'(q_n^*) = p^*$$

We find again that congestion pricing induces optimal usage of the network (Result 6 in Section 3).

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B.4 Optimal Capacity Expansion

Consider now optimal capacity expansion. As in Appendix A, denote $C(.)$ the cost of capacity K. As before we have:

Theorem 3   *1. The marginal value of capacity is:*

$$\eta(K) = p\frac{Q}{K}$$

2. $\mathcal{V}(K)$ is concave in K.

Proof. apply the envelope theorem:

$$\frac{d\mathcal{V}(K)}{dK} = \frac{\partial \mathcal{V}(K)}{\partial K} = nD'(Y)\frac{Q}{K^2} = \frac{nD'(Y)}{K}\frac{Q}{K}$$

Remembering that:

$$\frac{dY}{dK} = -\frac{Q}{K^2} = -\frac{Y}{K}$$

we have:

$$
\begin{aligned}
\frac{d\eta}{dK} &= \frac{d}{dK}[\frac{n}{K}YD'(Y)] \\
&= -2\frac{n}{K^2}YD'(Y) - \frac{n}{K^2}Y^2D''(Y) \\
&= -\frac{nY}{K^2}[2D'(Y) + YD''(Y)]
\end{aligned}
$$

If we assume that $2D'(Y) + YD''(Y) \geq 0$ ($D''(Y) \geq 0$ is a sufficient condition), we have: $\eta'(K) \leq 0$, hence the second claim of the theorem. ∎

The intuition is similar to the previous case: increasing capacity reduces delay (congestion) hence raises the net surplus from network usage. However, network capacity presents decreasing marginal returns. From the definition of $\eta(K)$, we immediately have:

Corollary 3 *The revenue from congestion pricing equals the congestion rent (Result 7 in Section 3):*

$$pQ = K \times \eta(K)$$

We then determine the socially optimal capacity:

Corollary 4 *The socially optimal capacity K^* satisfies (Result 5 in Section 3):*

$$\eta(K^*) = C'(K^*) \tag{5}$$

Proof. As before, the social welfare is: $W(K) = \mathcal{V}(K) - C(K)$. With $\mathcal{V}(K)$ concave and $C(K)$ convex, the program is concave. The first-order condition (5) immediately follows. ∎

B.5 Congestion Rent and Optimal Network Expansion

Consider now the choice of capacity K by network providers. MacKie-Mason and Varian [10] assume that competing network providers compete by offering a pair delay and price to users. Formally, the timing is: at date $t = 1$, each network provider offers a pair $(p(D), D)$; at date $t = 2$, users choose their network, and their usage on the network. The following proposition characterizes the outcome of such competition:

Proposition 2 (MacKie-Mason and Varian) *The private optimum perfectly decentralizes the social optimum: (1) the private pricing rule is the optimal pricing rule, and (2) the private expansion rule is the optimal expansion rule (Result 8 in Section 3).*

Proof. McKie-Mason and Varian [10] suppose a symmetric equilibrium: all network providers offer the same pair $(d, p(D))$. If delay increases, the price decreases: $p'(D) \leq 0$. Let us first examine the consumer problem. The consumer chooses a network D, and a consumption q_n:

$$\max_{q_n, D} \{u(q_n) - D - p(D)q_n\}$$

The first-order conditions are:

$$\begin{cases} u'(\hat{q}_n) = p(D) \\ -1 = p'(D)q_n \end{cases}$$

Adding up the later first-order conditions, we obtain:

$$-n = p'(D)Q \tag{6}$$

Equation (6) pins down $p'(D)$. With a limit condition, such as $p(\infty) = 0$, consumer optimization determines $p(D)$. Network providers then simply choose D, or equivalently K and Q:

$$\max_{K, Q} p(D(\frac{Q}{K}))Q - C(K)$$

The first-order conditions are:

$$\begin{cases} \frac{\partial \pi}{\partial Q} = 0 = p'(D(Y))D'(Y)Y + p(D(\frac{Q}{K})) \\ \frac{\partial \pi}{\partial K} = 0 = -p'(D(Y))D'(Y)Y^2 - C_K(K) \end{cases}$$

Substituting (6) into $\frac{\partial \pi}{\partial Q} = 0$, we obtain the private pricing rule:

$$p(D) = \frac{n}{K}D'(Y)$$

This is exactly the optimal pricing rule.
Then, multiplying (6) and the pricing rule, we obtain:

$$-p'(D)D'(Y)Y = p(D)$$

Substituting into $\frac{\partial \pi}{\partial Q} = 0$, we obtain the private expansion rule:

$$p(D)\frac{X}{K} = C_K(K)$$

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This is exactly the optimal expansion rule (5).

■

MacKie-Mason and Varian [10] also observe that, with constant marginal costs $C' = c$, the marginal equation (5) implies:

$$\pi'(K) = \frac{1}{K}(p(D)X - cK)$$

They conclude that, if the marginal profit is positive, the revenues from congestion fees exceed the cost of capacity expansion. This is true if the fixed-costs of capacity expansion are equal to zero. With positive fixed costs, the equality at the margin does not necessarily imply equality of the functions.

B.6 Congestion Rent and Under-investment

The above result stands in sharp contrast with the analysis presented for power networks. The crucial difference between both models is the assumption by MacKie-Mason and Varian [10] that network providers *compete* to offer service. Suppose instead that the network provider is a monopoly, and further assume that the regulator imposes he charges the optimal congestion price $p = \frac{n}{K}D'(Y)$. We have:

Proposition 3 *The monopolist network provider underinvests in capacity expansion (Result 8 in Section 3).*

Proof. From Corollary 3, the monopolist revenue is:

$$R(K) = \eta(K)K$$

As before, the marginal revenue for the monopolist is:

$$R'(K) = \eta(K) + K\eta'(K)$$

With $\eta'(K) \leq 0$, underinvestment obtains. ■

In other words, MacKie-Mason and Varian [10] show that, *if network provision is competitive*, congestion pricing leads to optimal expansion. ■
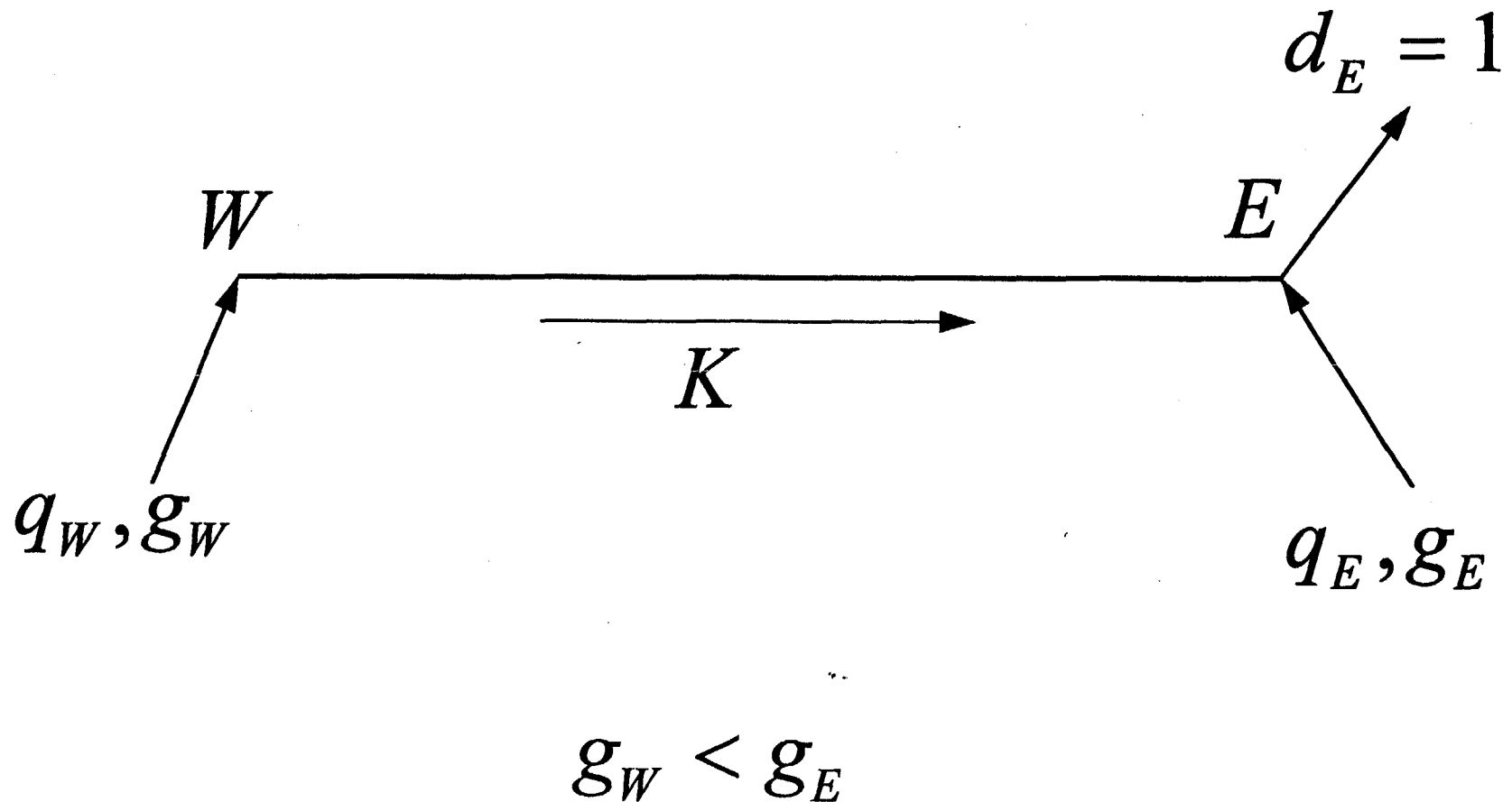
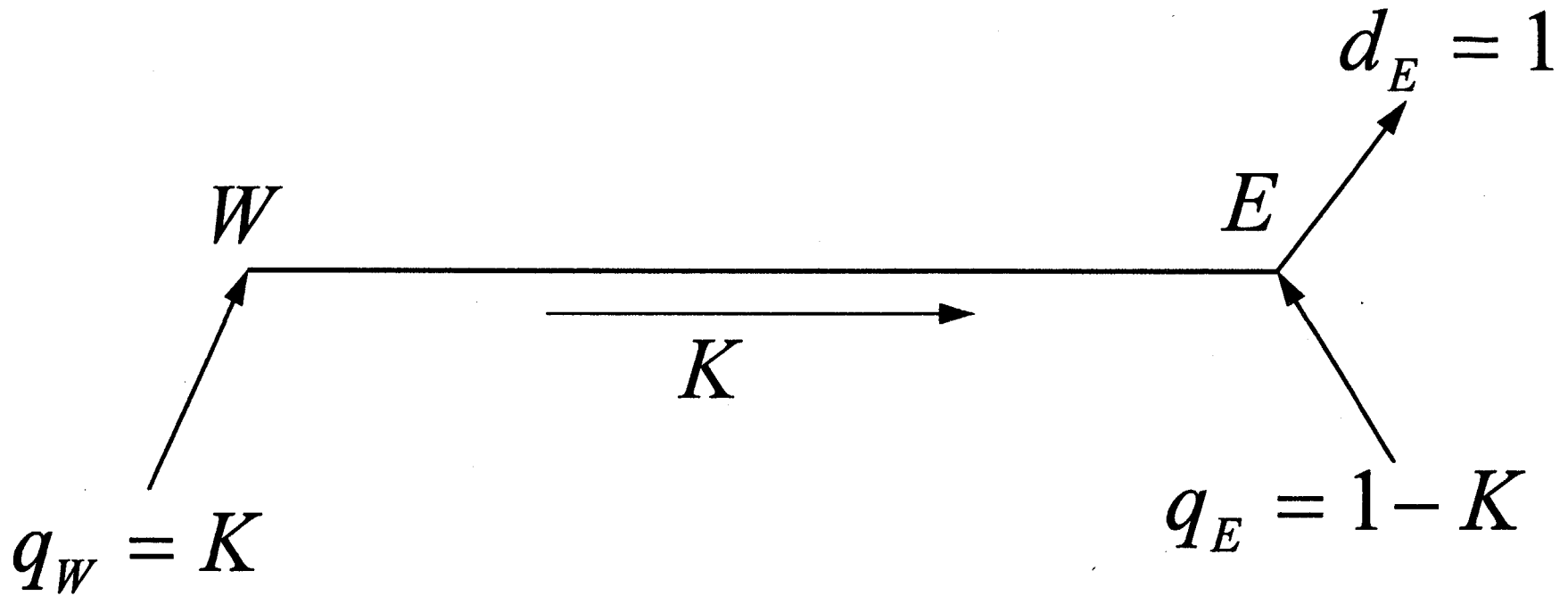# Figure 1: A Simple Power Network

$d_E = 1$

W

E

K

q_W, g_W

q_E, g_E

$g_W < g_E$

Figure 2: Optimal Dispatch

$$d_E = 1$$

$$W \qquad E$$

$$K$$

$$q_W = K \qquad q_E = 1 - K$$

$$\eta(K) = g_E - g_W$$

Figure 3: Marginal Value of Capacity

$$\eta(K) = g_E - g_W$$
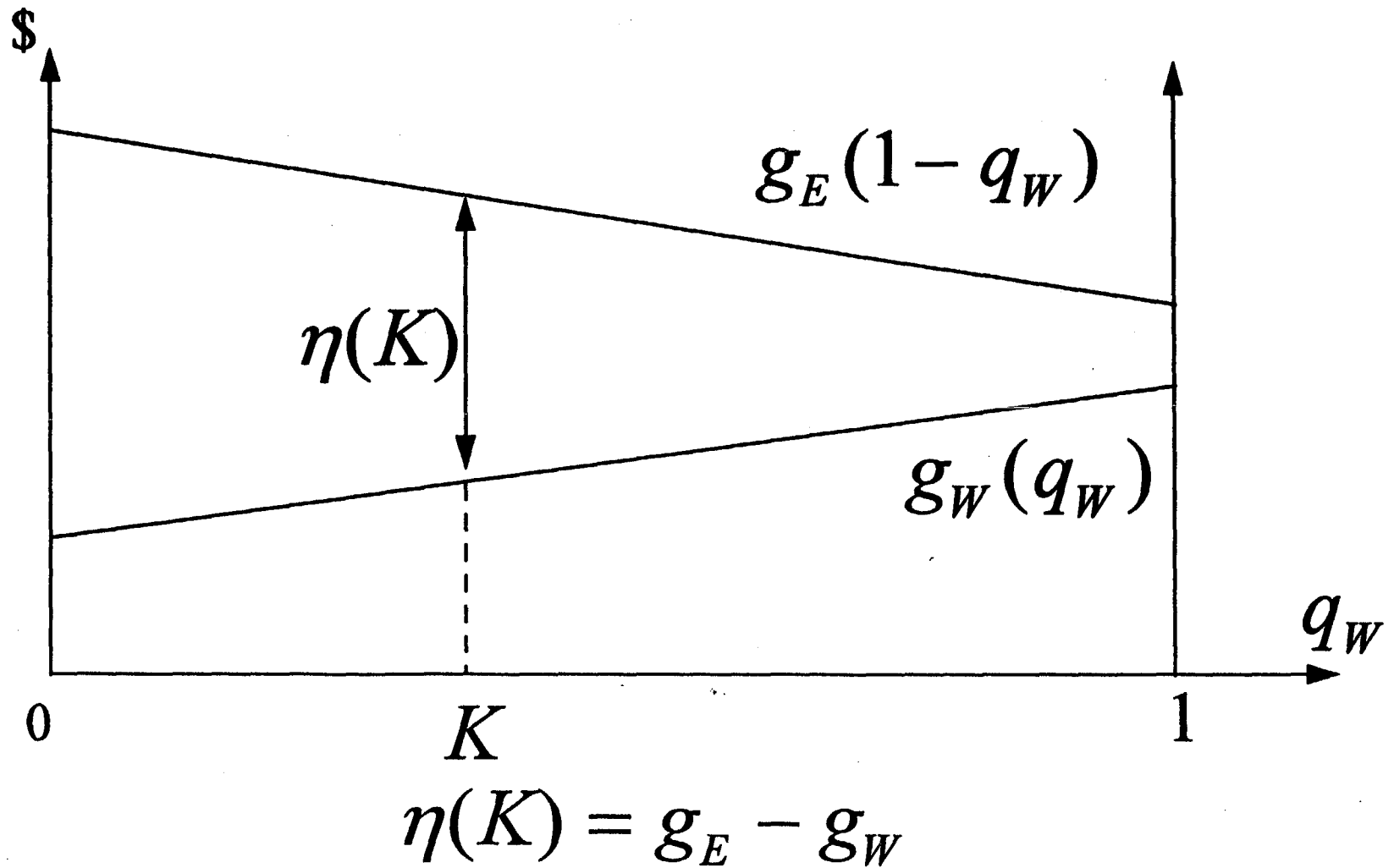
Figure 4: A Simple Internet Network

$$D = \frac{q_1 + q_2}{K}$$
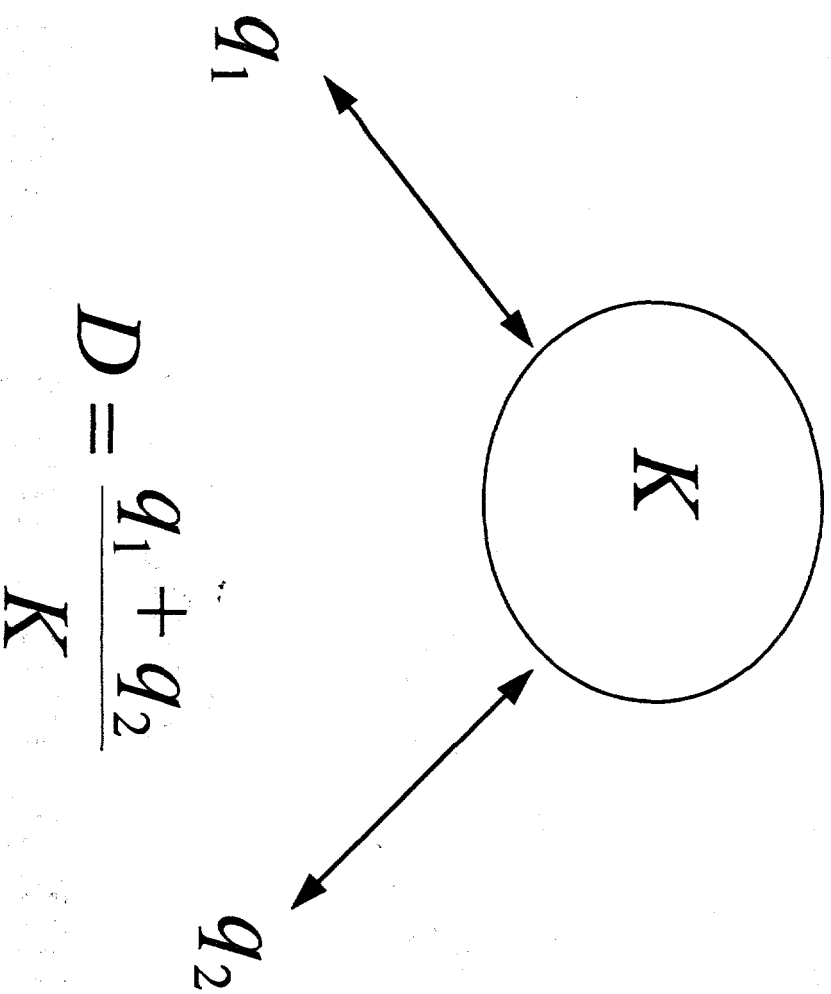
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