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The Impact of High Spectrum Costs on Mobile Network Investment and Consumer Prices

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The Impact of High Spectrum Costs on Mobile Network Investment and Consumer Prices

By **Richard Marsden**, **Hans-Martin Ihle**, and **Peter Traber**

Introduction

Auctions are now the standard approach for allocating spectrum licences for mobile use in many countries. A key justification for using auctions is the potential to deliver an efficient allocation of a scarce resource. Auctions also raise revenues, though the level of revenues has varied widely across countries. Researchers and policymakers have claimed that spectrum licence fees are sunk costs and should therefore have no impact on subsequent investment and consumer pricing decisions; however, recent work from the field of financial and behavioural economics contradicts the notion that sunk costs have no impact on a firm's behaviour. This paper provides statistical evidence that links high spectrum costs to lower network investments and higher consumer prices, suggesting that excessive prices for spectrum licences may have an adverse impact on consumers. We estimate a demand function for mobile, which allows us to quantify the lost consumer surplus. Our results suggest that lost consumer surplus far outweighs the gain in auction revenues.

Review of Academic Literature

In this section, we provide an overview of the academic literature on the impact of high spectrum costs.

Sunk Cost Argument

A number of researchers to date have posited that high spectrum licence fees are sunk costs and do not have an impact on subsequent investment and consumer pricing decisions. For example, Kwerel (2000)[1] and Wolfstetter (2001)[2] have argued that spectrum auctions are one-off transactions and that spectrum licence prices are thus sunk costs. According to this argument, spectrum costs are inescapable and do not vary with output or even if a firm fails. Using data from different markets in the US, Kwerel (2000) finds no evidence that suggests that higher spectrum costs lead to higher prices for consumers.

Hold-Up Problem

Although standard economic theory predicts that sunk costs are irrelevant to investment and pricing decisions, this theory is predicated on the notion that such decisions do not influence future choices. This simplistic interpretation of licence fees as sunk costs, however, does not consider the dynamic effects that high spectrum costs have over the long term. The sunk cost argument ignores the repeated nature of auctions and investments into the mobile sector. When spectrum is priced above true market value, it reduces the firm's profits, which, to a large extent, are the returns on the investments that it has already made (for example, in its network) and that are now sunk. In the short run, operators that need more spectrum may decide that they have little choice but to accept such terms. In the long term, however, they will respond by lowering their expectation of returns on future investments, which will reduce overall investment and may even lead to market exit or consolidation if operators cannot earn sufficient returns on their investments. In the economic literature, this phenomenon is referred to as the "hold-up problem".[3]

Pecking-Order Theory

The pricing structure for spectrum is fairly unique. Spectrum sold in auctions usually requires a large upfront payment followed by smaller annual fees. The upfront payment is generally financed internally. High upfront payments therefore reduce internal funds available for other projects. According to the pecking-order theory developed by Myers and Mailuf (1984), the cost of financing increases with asymmetric information.[4] Internal funding is cheaper than external funding, as external providers of finance have much less information about these investments than the mobile operator and thus require a higher risk premium. Using external sources to fund these other projects may mean that they are no longer profitable, as returns may be insufficient to cover the higher risk premium.

Internal Financing Constraints

Globally, the mobile market is characterised by a number of multinational companies that operate in a large number of countries. Each company's headquarters has a finite budget available that it can allocate to different regional markets. With this structure in place, it is quite natural that funds are diverted from less attractive markets to markets with higher expected profitability.[5] Profitability of sunk investments is directly linked to spectrum costs. Artificially high spectrum costs in a country can therefore lead headquarters to allocate less to a high spectrum-cost market in the future. McAfee, Mialon, and Mialon (2010)[6] refer to this effect as "de-escalation" or "reverse sunk-cost effect" owing to financial constraints.

Bauer (2001)[7] makes a similar argument that high upfront spectrum costs force operators to adjust their investment strategies in terms of rollout of network capacity, due to tightened financial constraint and a worsened credit standing.

Behavioural Economics

In classic microeconomic theory, firms maximise profits by setting prices such that marginal revenue equals marginal cost.[8] Sunk costs, such as upfront spectrum fees, do not feature in this version of the price-setting process. Some early studies on the relationship between spectrum fees and consumer prices appeared to confirm this assessment;[9] however, more recent research in the field of behavioural economics challenges this classical view. In particular, in sectors with imperfect competition in which firms have some degree of flexibility over the prices they set, researchers have observed a tendency for prices to inflate over the theoretically efficient price if sunk costs are increased.

In one simulated experiment, Offerman and Potters (2006)[10] found that upfront fees for entry licences produced high short-term prices for consumers in markets with a small number of participants. In addition, the average price for consumers remained high long after the upfront entry fee was paid. They then examined if the increase in prices was specific to the allocation mechanism (either a fixed fee or an auction). The results showed that the method of allocation did not affect price levels, but the simple presence of an entry fee in a market with limited competition increased prices paid by consumers.

In another experimental study, Buchheit and Feltovich (2001)[11] showed that varying sunk costs produce different outcomes for consumer prices. Specifically, the experiment was set up in a way that the market could either produce a stable high-price outcome or a stable low-price outcome. In situations of high sunk costs, firms tended to select the high-price equilibrium whereas in situations of medium-to-low sunk costs, firms tended to select the low-price equilibrium. Overall welfare, therefore, could be described as following a "reverse U" pattern, where moderate sunk costs produced the optimal level of welfare.

Recent Literature Investigating Negative Impact of High Spectrum Costs

Park, Lee, and Choi (2010)[12] present empirical evidence that appears to support the sunk-cost argument. Using a dataset of 21 Organisation of Economic Co-Operation and Development (OECD) countries that assigned 3G spectrum both via auctions and beauty contest, the authors do not find any statistically significant result that relates the level of licence fees to an increase in revenues. Similarly, Cambini and Garelli (2017)[13] present evidence that spectrum availability and fees are not significantly correlated with mobile industry revenues.

Both studies use revenues rather than actual consumer prices. This is likely due to the fact that revenue data is easily available. A key concern with using revenues is that it includes the consumer response to consumer prices. If consumer prices are high, the quantities consumed (such as data or minutes) are likely to be low and vice versa. So a country with low consumer prices and high usage could have very similar average revenue per user (ARPU) as a country in which consumer prices are high and usage is low. Arguably, these two countries are very different in terms of the benefits enjoyed by consumers.

What is most surprising about the Cambini and Garelli study (2017) is that it actually finds a link between higher spectrum fees and higher revenues using straightforward regression techniques. The authors claim, however, that licence fees are endogenous[14] and that a more complex regression is needed. To remove this supposed endogeneity, they then use the Arellano Bond Generalized Method of Moments (GMM) estimator, which somehow also removes the impact of spectrum fees on revenues.[15]

Hazlett and Muñoz (2009)[16], on the other hand, show that the key determinants of social welfare generation in mobile markets are the amount of spectrum allocated to mobile operators and the level of competition in the market.

The aim of this study is twofold:

- Provide simple econometric evidence for a link between spectrum costs, investment, and consumer prices; and
- Adapt the model developed by Hazlett and Muñoz (2009) to the data-centric 4G market and to include spectrum costs as an explicit variable in the supply equation.

Link Between Spectrum Costs and Network Investment

To test whether there is a link between spectrum costs and network investment, we require proxies for the total financial burden on operators and their investments in next-generation networks. We focus on the 4G era, using data from 2008 to 2016.

Measuring Spectrum Cost

In order to make comparisons of spectrum costs across countries, prices are typically expressed as a price per MHz/pop (i.e., price divided by MHz and total population) and measured in a common currency, adjusted using either real or purchasing power parity exchange rates. This approach is appropriate when comparing prices for similar frequency bands; however, this approach may not capture the financial burden and the strain on internal financing, as it does not consider the volume of spectrum sold and the aggregate spend. Since 2008, many countries have sold spectrum in multiple bands, which have together imposed a large aggregate financial burden on operators. For example, in 2012, winning bidders spent almost US$4.7 billion or US$280 per pop on spectrum across five bands in the Netherlands. To capture this, we consider total spectrum costs across all bands on a per pop basis.[17]

Measuring Investment in 4G Networks

We consider total industry expenditure rather than individual operator expenditure, owing to the difficulties of compiling comparable investment data for individual operators. Many national mobile operators are subsidiaries of larger operators and not required to publish disaggregated data on their annual capital expenditure and operating expenditure. Therefore, we cannot directly observe expenditure on 4G networks for operators or countries worldwide. Instead, it is necessary to identify a proxy for network investment. To do this, we developed a "wireless score" that measures the quality and uptake of next-generation data services in each country using actual user data.

Our wireless score is the product of the following three components:

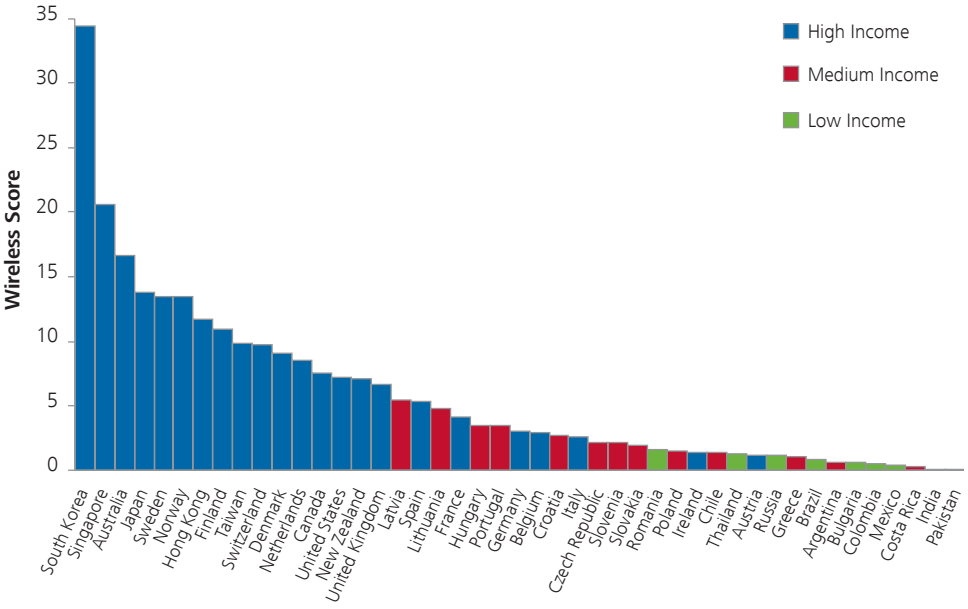
- **3G/4G coverage as recorded by Open Signal**. This is measured as the percentage of time when users have access to a high-speed network. We believe this, rather than geographic coverage, is a better proxy for comparing the actual ability of users to access mobile data, given the huge differences in population dispersal among countries. We do not differentiate between 3G and 4G coverage, as—in many countries—3G may provide a near-4G experience.[18]

- **Average speed as recorded by Open Signal**. This is measured in megabits per second based on observed user experience;[19] and

- **4G subscriber share**. We include 4G subscriber share as a percentage of total population in the score so as to ensure that the score reflects progress in 4G rollout, as opposed to just 3G.[20]

We include both coverage and speed because they are the main determinants of quality of service. To arrive at a single score, we multiply the three numbers: in effect, our wireless score is a weighted measure of mobile data speed. Figure 1 shows the wireless score for each country included in our study.

Figure 1. **Wireless Score by Country**



Source: NERA Economic Consulting, using data from OpenSignal.com and TeleGeography GlobalComms database.

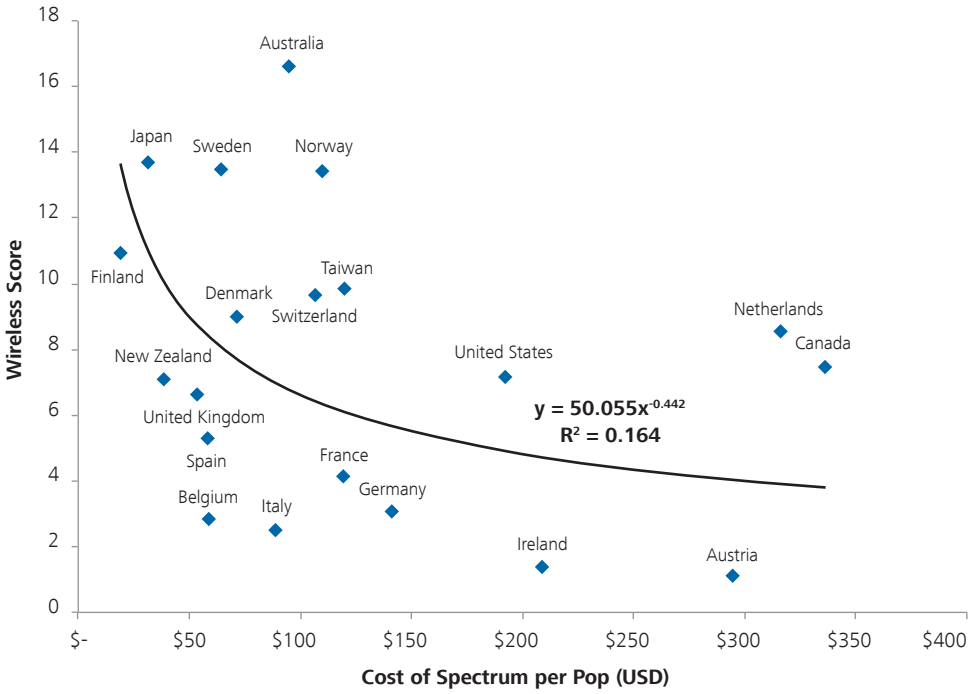
Countries differ widely in their uptake of 4G services and in the coverage and speeds experienced by users. Countries with higher incomes typically have substantially higher wireless scores than countries with medium incomes, which in turn typically have substantially higher scores than low-income countries. The disparity in wireless scores is hardly surprising, given that 4G technology was first launched in high-income countries, while many low-income countries in our sample have only recently launched services. Moreover, consumers in high-income countries have greater ability to pay for and more scope to use next-generation mobile data services. We determined that the best way to account for these differences was to divide the sample into three groups of countries: high income; medium income; and low income, based on GDP per capita.[21]

Findings

For all three country groups, we find a correlation between lower spectrum costs and higher wireless scores. These results support the hypothesis in the academic literature that high input costs suppress investments. They directly contradict the more simplistic hypothesis that licence costs do not affect investment because they are sunk costs. Although spectrum cost is one of a number of factors that causes differences among countries in network investment, the results indicate that they are an important factor.

The relationship between spectrum costs and wireless score for high-income countries is reported in Figure 2.

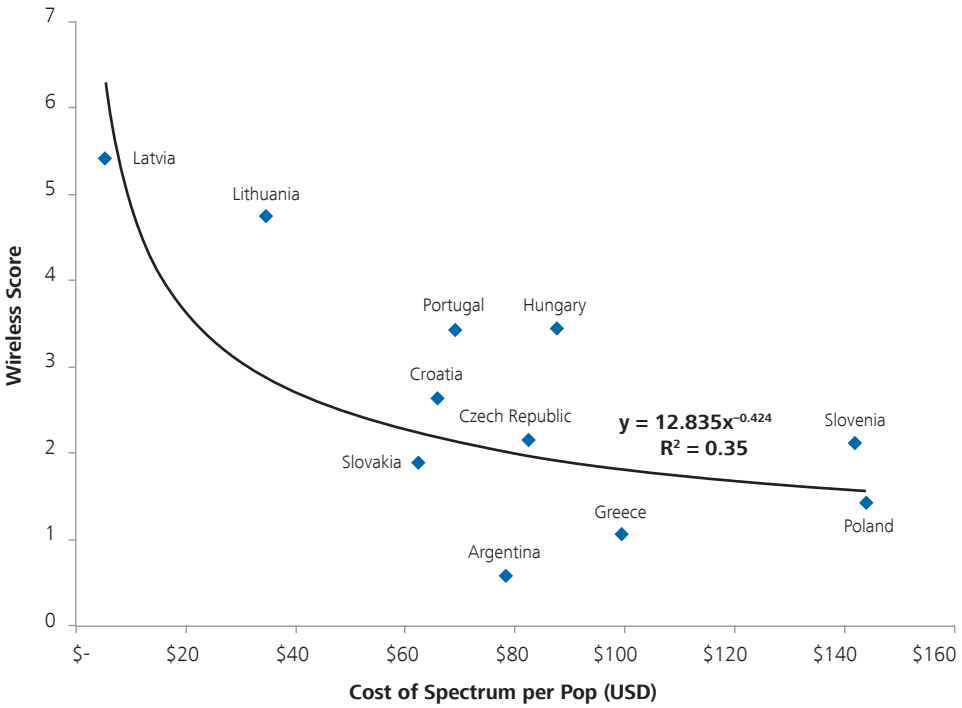
Figure 2. **Spectrum Costs and Wireless Score in High-Income Countries**



Notes: South Korea is located off of the top left-hand side of the graph; it has an exceptionally high wireless score (29.5) and modest cost of spectrum per pop (US$53). We excluded Hong Kong and Singapore from our analysis, as they are city-states and much easier to cover with 4G.
Source: NERA Economic Consulting using data from OpenSignal.com and TeleGeography GlobalComms database.

The relationship between spectrum costs and wireless score for medium-income countries is reported in Figure 3. The relationship shown here is even stronger than for high-income countries, but the sample is smaller: only 12 countries, 10 of which are in Europe.

Figure 3. **Relationship Between Spectrum Costs and Wireless Score in Medium-Income Countries**



Notes: Excludes Chile because it is an outlier owing to late adoption of 4G, which depressed its wireless score.
Source: NERA Economic Consulting with data from OpenSignal.com and TeleGeography GlobalComms database.

We also explored the relationship between spectrum costs and wireless scores for low-income countries. This sample of countries is small and much more heterogeneous than the other groupings, for example ranging from Pakistan, with a GDP per capita of US$1,450, to Mexico, with a GDP per capita of US$9,010. Although the observed relationship is consistent with the hypothesis (and strongly significant if two extreme outliers from the sample of 10 countries are dropped), all of the countries have low wireless scores. Given that many of them only recently launched 4G services, it would be premature to place any great weight on observed differences between them.

Link Between Spectrum Costs and Consumer Prices

To test whether there is a link between spectrum costs and consumer prices, we extended our country-by-country analysis to consider the relationship between spectrum costs and consumer prices for mobile data. As above, we set out our methodology and source data, and then present our findings. For both high- and medium-income countries, we observe a significant statistical link between higher spectrum costs and higher consumer prices for data.

Methodology and Source Data

In this section, we use spectrum cost as measured on a per MHz/pop basis, which more closely reflects the cost of spectrum capacity as an input into providing mobile data services.

As mentioned in the second section of this paper, studies so far have focused on revenues in the mobile sector. Such studies may be misleading, however, as revenues include a quantity response from consumers and may therefore misrepresent the impact of spectrum costs on consumer prices. We collected prices for wireless data for each country in our study in 2016. Wireless plans vary substantially across countries and across mobile operators. To make them comparable and to identify a representative price for 1 GB of data, we selected (or constructed with add on "data packs") a "representative plan" for every mobile network operator (MNO) within a country.[22] The price of each MNO's plan was then divided by the number of gigabytes in the representative plan. Each country's representative price for 1 GB of data was then calculated using the weighted average (subscriber share) of all of the representative plans available in the country.[23]

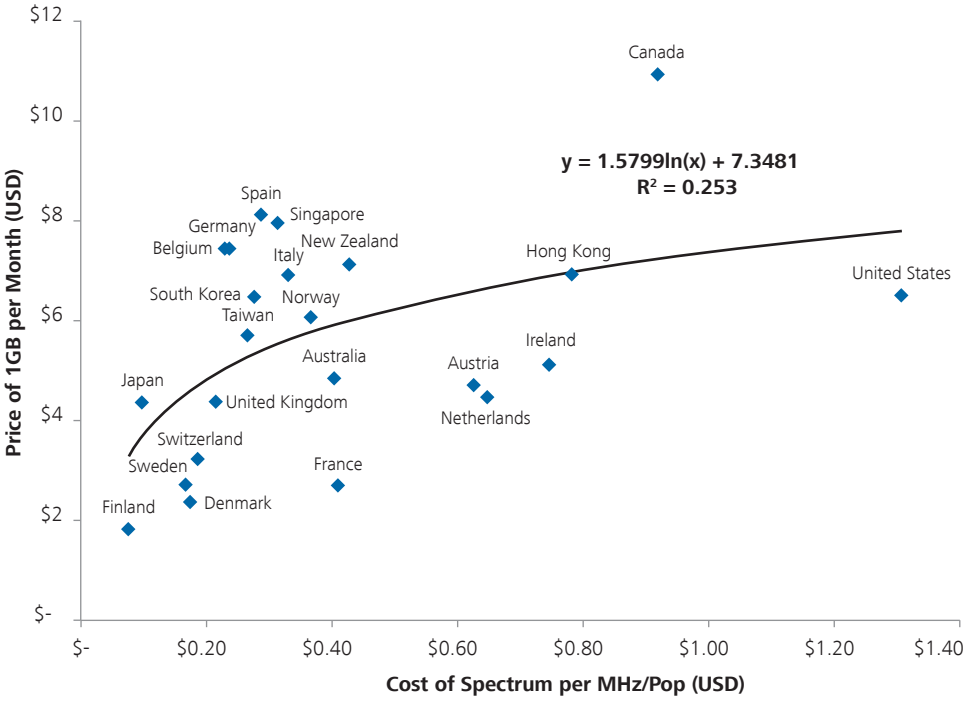
Findings

We divide our sample into three groupings based on GDP per capita, to avoid distortion of the results by the relationship between price levels and ability to pay in countries with very different income levels.

For all three country groups, we find a correlation between lower spectrum costs and lower consumer prices for data services. These results support the hypothesis that high input costs suppress incentives for price competition.

Figure 4 shows the negative relationship between the cost of spectrum and data prices in high-income countries. The relationship is nonlinear, implying that proportionally greater gains for consumers through lower prices are possible as spectrum costs are reduced.

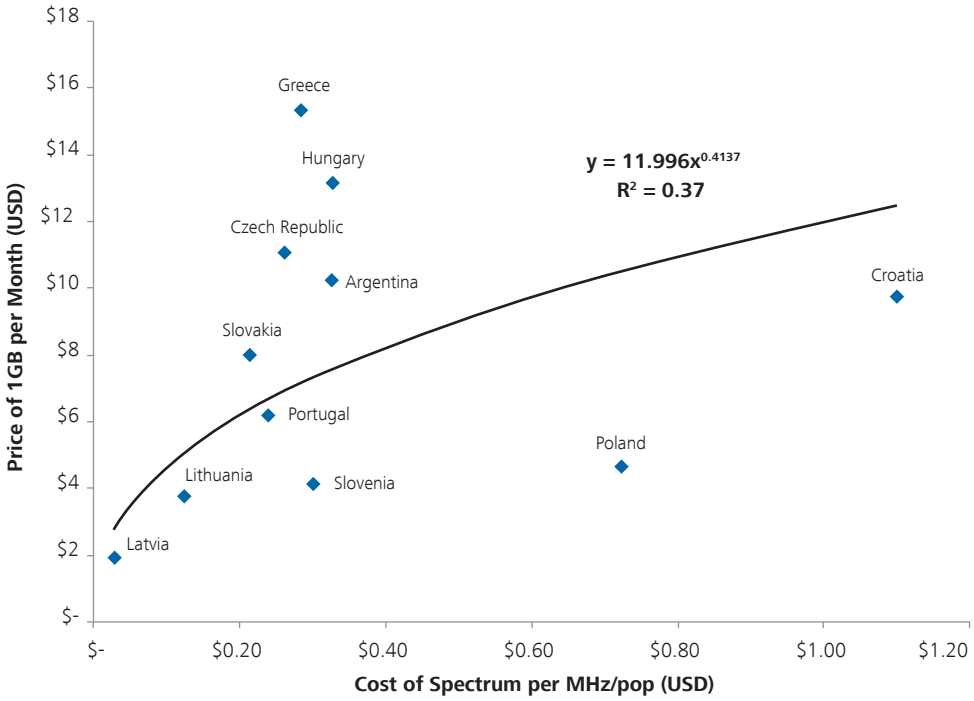
Figure 4. **Price and Spectrum Cost Relationship in High-Income Countries**



Source: NERA Economic Consulting.

The relationship is even stronger for medium-income countries, as illustrated in Figure 5, albeit with a smaller sample size.

Figure 5. **Price and Spectrum Cost Relationship in Medium-Income Countries**



Source: NERA Economic Consulting.

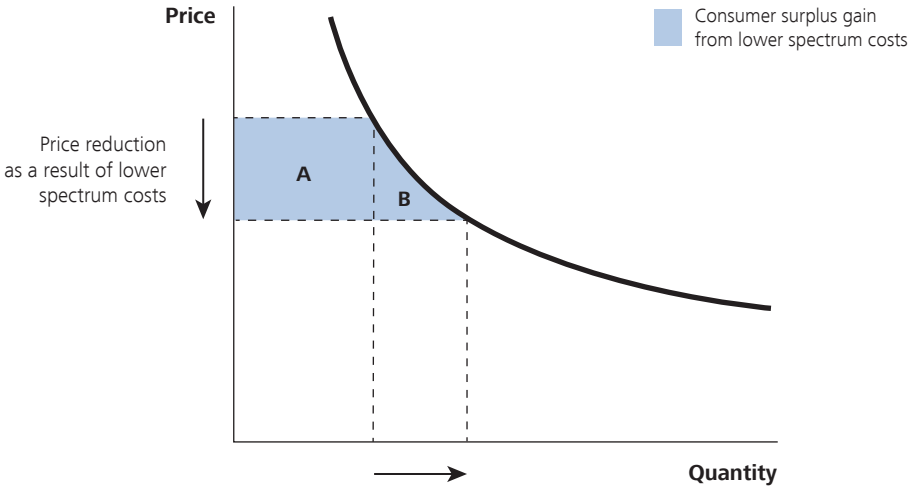
For low-income countries, the relationship is in the same direction but not statistically significant. As with our investment analysis, we similarly think our sample of low-income countries is too small and heterogeneous and launched 4G too recently to place any great weight on observed differences between countries.

The correlations shown here obviously do not control for other factors that may be associated with both the cost of spectrum and consumer prices. In the following section, we estimate a supply equation that controls for these factors. The link between spectrum costs and consumer prices, however, persists.

Welfare Study

We have shown that a reduction in spectrum costs can support a reduction in consumer prices for mobile data. This, in turn, should lead to an increase in the quantity of data services consumed. We illustrate this using a standard demand curve in Figure 6. The gain in surplus for consumers is equal to the blue shaded area. This consists of a transfer of surplus from producers to consumers (area A) owing to price competition, and previously unrealised surplus (B) generated by the increase in the quantity consumed. In effect, surplus that producers would have otherwise retained in order to fund spectrum costs (area A) is, in the counterfactual scenario of lower spectrum costs, competed away through lower prices. The resulting expansion in consumption also enables society to reclaim additional surplus (area B).

Figure 6. **Consumer Surplus Impact of Price Reduction**



Building on our analysis of the relationship between spectrum costs and prices for mobile data, it is possible to construct an econometric model of demand for mobile data. We take the methodology developed by Hazlett and Muñoz (2009) to model demand for mobile voice in the early 2000s and apply this to mobile data in 2016. The model takes into account the cost of spectrum, data prices, and data consumption (quantity), as well as a number of explanatory variables for demand, including GDP per capita, urbanisation, and mobile market concentration.

We follow the methodology developed by Hazlett and Muñoz (2009) for mobile voice to estimate a demand curve for mobile data services in 2016. Our model is based on data from 32 countries.

The consumer welfare produced through consumption of a good is a function of both the price paid for the good and the quantity consumed. Price and quantity are therefore the main variables in the model. These variables are endogenous, as they are jointly determined by the interplay of demand and supply in the market: the price that consumers pay affects the quantity consumed and the quantity consumed affects the price that consumers pay. In econometrics, this is referred to as a "reverse feedback effect", and ordinary regression techniques have been shown to provide poor results in these situations. We therefore use an Instrumental Variable (Two Stage Least Squares) model to estimate the demand for mobile data. In the first stage, we estimate price as a function of a number of variables that mainly impact the supply of mobile data (not demand).[24] In the second stage, we estimate the demand function or the quantity of mobile data consumed as a function of a number of variables affecting demand, including the predicted price from the first stage. Using the predicted price rather than the observed price removes the feedback effect.

The inputs used in the model are summarised in Table 1. We also considered other inputs. Wi-Fi availability was tested as a substitute for mobile data usage, but it was not statistically significant and was removed.[25] In the price equation, we considered labour costs, as well as industrial electricity costs. Labour costs were highly correlated with GDP and thus dropped, while industrial electricity costs were not statistically significant in the price equation.

Table 1: **Inputs into Econometric Model**

Variables	Description and Data	Role in Model
Quantity Consumed (GB per Month)	The average amount of data per month consumed by wireless subscribers within a country. Data was collected from Tefficient reports and Cisco VNI data.	Second Stage Dependent Variable
Price (USD per GB/ Month)	The price paid by consumers in a country. In order to standardise across countries, we created a representative mobile plan for each country, based on information collected from local operator websites in September 2016. The prices are expressed in PPP-adjusted US dollars. This variable is the same as used in the price analysis presented in the fourth section of this paper.	Second Stage Endogenous Variable and First Stage Dependent Variable
GDP per Capita (USD/Pop)	A higher GDP per capita implies higher disposable income for consumers and a higher demand for data; however, GDP per capital also implies more network maturity, which can depress consumer prices. We use data from the International Monetary Fund's 2015 database.	Independent Variable in First and Second Stage Regressions
Urbanisation (% Urban Pop)	Urbanisation is included as a proxy for the difficulty of rolling out a wireless network in a country. In general, higher urbanisation means that greater capacity is required in small crowded areas. This requires higher densification of the network (more cells to cover a small area) and can increase the cost of sites (higher rents, more stringent planning regulations). On the other hand, lower urbanisation means that more cells are required to cover the same population. We use data from the World Bank Database.	Independent Variable in First Stage Regression
Herfindahl-Hirschman Index (HHI)	HHI is a measure of market competition, and is a proxy for the pricing power of operators. Increasing competition in a market is associated with lower prices owing to the greater scope for consumers to move to an alternate provider. HHI is derived from total subscriber share by country using data from the TeleGeography GlobalComms database.	Independent Variable in First Stage Regression
Cost of Spectrum (USD per MHz/ Pop)	The purpose of the model is to understand the impact of spectrum cost on consumer welfare via the impact on consumer prices. We use the same spectrum cost data as used in our analysis in the fourth section of this paper.	Independent Variable in First Stage Regression

We use the following specification for the price equation (first stage):

$$\ln(price) = \beta_0 + \beta_1 \ln(gdppc) + \beta_2 \ln(urbanisation) + \beta_3 \ln(hhi) + \beta_4 \ln(spec_cost)$$

The Demand Equation (second stage) is defined as:

$$\ln(quantity) = \beta_0 + \beta_1 \ln(\overline{price}) + \beta_2 \ln(gdppc)$$[26]

The results of the regression are summarised in Table 2.

Table 2: **Regression Results**

	First Stage Regression	Demand Equation
Independent Variable	Price	Quantity
Explanatory Variables:		
Constant	4.24**	-0.78
Price (IV)	–	-1.15***
GDP	-0.60***	0.29*
Urbanisation	1.15**	
Spectrum Cost	0.37***	
HHI		0.78*
R^2	50%	54%

Notes: Significance levels: *** at the 1% level, ** at the 5% level, and * at the 10% level.

We find that:

- Spectrum costs have a statistically significant positive impact on prices paid by consumers.
- Prices in countries with higher GDP per capita are generally lower, which can be attributed to the fact that mobile networks are more mature in developed countries and thus the cost of delivering a GB of data is lower.
- In countries with higher urbanisation, prices are generally higher. This may reflect the increased focus on investment in urban capacity to meet 4G demand, and the high rental and planning costs of urban sites.
- Higher market concentration (as measured by the HHI index) is associated with higher consumer prices, but the statistical relationship is much weaker than for the other factors (only significant at the 10% level).

- The quantity of data consumed is negatively affected by price. Higher prices lead to less data consumed. Note that data demand is elastic; if the price increases by 1%, the quantity demanded goes down by more than 1%, which means consumers are sensitive to prices.

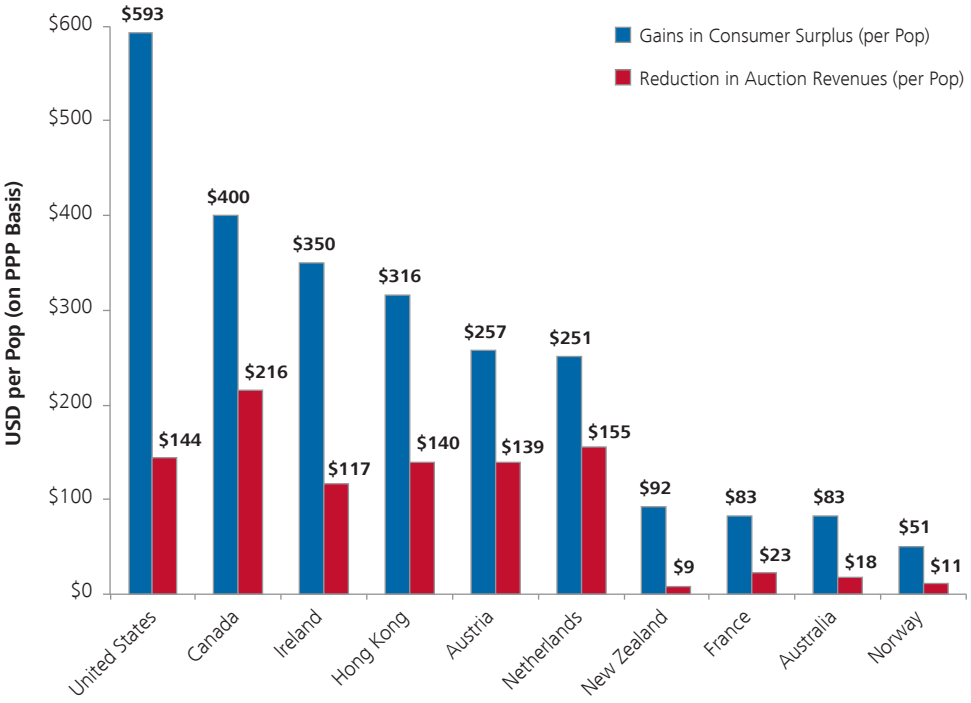
Using the system of equations from the regression, we simulated the shift in the demand curve from reducing spectrum costs and used this to predict the change in consumer surplus. To simulate the shift in the demand curve, we divided countries into peer groups based on GDP per capita. The cost of spectrum of all countries with a cost of spectrum above their respective group median was lowered to the peer median. A new demand curve was constructed for each country using the variables and coefficients from the original model, except for the decreased cost of spectrum. Once the new demand curve was constructed, we calculated the change in consumer surplus between the original and new demand curves using standard economic techniques, as illustrated in Figure 6. Lost auction revenues, as a result of the price reduction, were set against the gains in consumer surplus, so as to determine the net benefits for society. All values are expressed in US dollars on a purchasing power basis.

We use this model to calculate the potential welfare gains from lower spectrum costs (via lower data prices), as illustrated in Figure 6. Specifically, for each country, which has a cost per MHz/pop above the median for its peer group, we ask what gains in consumer surplus are possible if the cost of spectrum was reduced to the median level. For peer groups, we use the same three categories—high, medium, and low income—based on GDP per capita.

Across our sample of 32 countries, 15 had costs above the median level for their peer group. We estimate the aggregate gain in consumer surplus from reducing spectrum costs to the median level across these countries to be US$445 billion. This gain would come at the expense of reduced government revenues of US$192 billion. Thus, the net welfare gain for consumers in these countries from lower spectrum costs would be US$253 billion in total or US$118 per person. All of these figures are in purchasing power terms (with real exchange rates, our numbers would be lower).

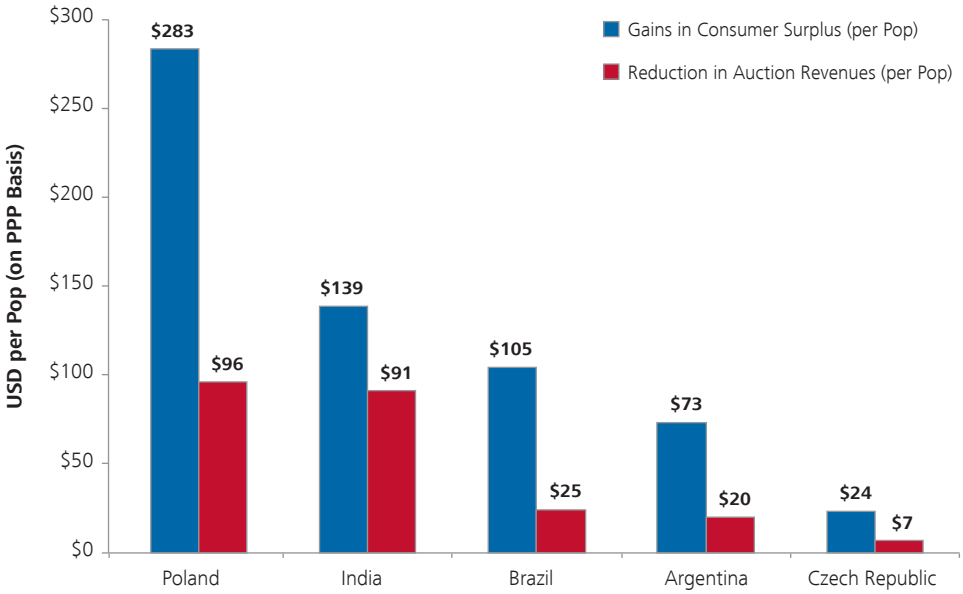
Figure 7 and Figure 8 provide a breakdown of the estimated welfare effects for countries in our sample with above median prices. Individual country calculations should be interpreted with caution, as our global model necessarily cannot account for local factors that may push the true market price up or down.

Figure 7. **Implied Scope for Net Gains in Consumer Surplus from Lower Spectrum Costs for Selected High-Income Countries**



Source: NERA Economic Consulting, using data from various sources.

Figure 8. **Implied Scope for Net Gains in Consumer Surplus from Lower Spectrum Costs for Selected Medium- and Low-Income Countries**



Source: NERA Economic Consulting, using data from various sources.

Conclusion

We provide evidence for a link between high spectrum costs, and lower investments and higher consumer prices. This supports recent theoretical arguments that high spectrum costs are not a free lunch for governments. Instead, they likely harm both the industry and consumers.

Investment in mobile network infrastructure will be a key enabler of growth and competitiveness in national economies worldwide for the foreseeable future. Our results show that when policymakers plan spectrum awards, they should be focused on maximising welfare benefits over the long term, by stimulating competition and investment, rather than focusing on short-term revenue benefits. In recent years, many countries have launched ambitious national plans for ICT (information and communications technology) development. Timely award of mobile spectrum at prices that promote full allocation and efficient use should be a cornerstone of such plans.

Notes

[1] Evan Kwerel, Federal Communications Commission, Spectrum Auctions Do Not Raise the Price of Wireless Services: Theory and Evidence, 2000, available at: http://wireless.fcc.gov/auctions/data/papersAndStudies/SpectrumAuctionsDoNotRaisePrices.pdf.

[2] Elmar Wolfstetter, The Swiss UMITS Spectrum Auction Flop: Bad Luck or Bad Design?, 2001, available at https://www.google.com/search?q=Heidi+K.+Gardner%2C+PhD%2C+Distinguished+Fellow+in+the+Center+on+the+Legal+Profession+at+Harvard+Law+School+&ie=utf-8&oe=utf-8#q=The+Swiss+UMITS+Spectrum+Auction+Flop:+Bad+Luck+or+Bad+Design?

[3] Hold-up occurs when the return on one party's sunk investments can be expropriated *ex post* by another party. In the case of spectrum licences, the government can expropriate the returns on other sunk investments (such as in network infrastructure) made by a mobile operator by overcharging for access to spectrum. The hold-up problem has played an important role as a foundation of modern contract and organisation theory. The associated inefficiencies have justified many prominent organisational and contractual practices. See for example, William P. Rogerson, "Contractual Solutions to the Hold-Up Problem", *Review of Economic Studies*, Vol 59, 1992, p. 777-794.

[4] Stewart C. Myers and Nicholas S. Majluf, "Corporate financing and investment decisions when firms have information that investors do not have", *Journal of Financial Economics*, 13 (2): 187–221.

[5] Jeremy C Stein, "Internal Capital Markets and the Competition for Corporate Resources", *The Journal of Finance*, Vol. 52, 1997, p. 111-114.

[6] McAfee, Mialon, and Mialon, "Do Sunk Costs Matter?", *Economic Inquiry*, Vol. 48, No.2, 2010, p. 323-336.

[7] J. M. Bauer, "Spectrum auctions, prices and network expansion in mobile communications," in proceedings of the 29th Telecommunications Policy Research Conference, Alexandria, Virginia, 27-28 October 2001.

[8] Put differently, an operator will increase its profit by expanding production, provided that the revenue from producing an extra unit of a good or service exceeds the cost of producing that extra unit.

[9] Evan Kwerel, "Spectrum Auctions Do Not Raise the Price of Wireless Services: Theory and Evidence", FCC, 2000.

[10] Offerman and Potters, "Does Auctioning of Entry Licences Induce Collusion? An Experimental Study", *Review of Economic Studies*, Vol. 73, 2006, p. 769-791.

[11] Buchheit and Feltovich, "Experimental Evidence of a Sunk-Cost Paradox: A study of Pricing Behaivor in Bertrand—Edgeworth Duopoly", *International Economic Review*, Vol. 52, 2001, p. 317-347.

[12] M. Park, S.W. Lee, and Y. J. Choi. "Does spectrum auctioning harm consumers? Lessons from 3G licensing", *Information Economics and Policy*, 23, 2010, p. 118–126.

[13] C. Cambini and N. Garelli, "Spectrum fees and market performance: A quantitative analysis", *Telecommunications Policy* (forthcoming, 2017).

[14] Their argument is that operators may bid high in an auction in the expectation of higher revenues.

[15] With small sample sizes, different GMM estimators are known to produce very different results. The results in the study show that the coefficient estimates are unstable across different estimation techniques suggesting that the model is not particularly stable.

[16] See Hazlett and Muñoz, "A Welfare Analysis of Spectrum Allocation Polices", *RAND Journal of Economics*, Vol. 40, No. 3, 2009.

[17] NERA maintains its own database of prices for mobile spectrum awards for countries around the world. This includes data on both upfront fees from auctions or direct awards, and, where relevant, incorporates annual fees for awarded spectrum. We used these prices to construct an index of the total financial burden on mobile operators from spectrum purchases in each country where we had comprehensive award data for the 2008-2016 period.

[18] Coverage data is from OpenSignal.com (Q4 2015 data).

[19] Speed data is from OpenSignal.com (Q4 2015 data).

[20] Subscriber data is from the TeleGeography GlobalComms database (Q4 2015 data).

[21] We define high income as any country with GDP per capita above US$25,000, medium income as between US$11,000 and US$25,000, and low income as below US$10,000. We use 2015 data from the International Monetary Fund (IMF) to determine income by country.

[22] The representative plans were constructed to have approximately 10 GB of data per month, as well as the highest SMS/voice minute combination. We add SMS and voice, as these are usually included in mobile plans in most countries. For example, in the United States, there are no limits on these services, whereas, in some other countries, SMS and voice attract premium fees (e.g., Singapore). We would not be comparing like for like if we ignored relatively expensive voice and SMS add-on services in Singapore and only focused on data. We set a threshold of 15 GB per month for unlimited plans or for countries that set price based on speed (Finland), given typical usage rarely exceeds this level.

[23] Note that we intentionally chose not to use ARPU in this analysis. ARPU is not a good indicator for the prices that consumers face in different countries, as it includes a decision by users on how much to consume. For example, consumers in a high-price country may decide to consume very little data, whereas consumers in a low-price country may decide to consume a lot of data. Thus, the ARPU in two countries may be similar even though actual prices are very different.

[24] Note that in order to arrive at an unbiased estimate of the second function, we need to include all other variables included in the second function in the first function as well.

[25] We used the average time that handsets are connected to wifi networks as a proxy. Data from OpenSignal.com (Q4 2015).

[26] ln(*price*) are the *predicted* values from the price equation.

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