

WP FA5/2012

## The costs of electricity interruptions in Spain. Are we sending the right signals?

Pedro Linares, Luis Rey

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Pedro Linares\* and Luis Rey†

## Abstract

One of the objectives of energy security is the uninterrupted physical availability of energy. However, there is limited information about how much is the cost of energy supply interruptions. This information is essential to optimize investment and operating decisions to prevent energy shortages. In this paper, we estimate the economic impact of an electricity interruption in different sectors and regions of Spain. We find that in 2008 the cost for the Spanish economy of one kWh of electricity not supplied was around €6, which is much higher than the signals sent for the operation of the power system. This would mean that we are underinvesting in short-term energy security.

**JEL classification:** Q40; Q41; L94

**Keywords:** Energy security, electricity interruptions, value of lost load, Spain

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# 1 Introduction

Security of supply is considered as an important objective of energy policy in many countries around the world. Together with efficiency and sustainability, the European Union includes security of energy supply as one of the three pillars of its energy policy (European Commission (EC) 2008; European Commission (EC) 2006).

In particular, the focus on the security of supply of electricity has increased since the liberalization of the electricity sector in many countries. Theoretically, a liberalized market increases competition and, thus, leads to a more efficient outcome. However, in absence of a proper regulation, electricity suppliers may not have the incentives to ensure a socially optimal security of supply (Rodilla and Batlle, 2010). Batlle et al (2007) divide the security of electricity supply in three components:

- A short term level, which refers to the ability of existing generation capacity to meet actual load and support unexpected disturbances such as electrical short circuits.
- A medium term level, defined as the ability of the already installed capacity to supply electricity efficiently, and therefore, depends on generation and resource management decisions.
- A long term level, which refers to the existence of enough available capacity, both installed and/or expected, to meet demand.

Arguably, the medium term level is one of the most relevant and common. In the last years many countries have experienced electricity shortfalls due to this reason. In 2000 and 2001, California had a shortage of electricity that caused large economic losses. In Europe, the summer of 2003 was extraordinarily hot and dry; consequently, the energy demanded for air conditioners increased while hydro capacity to generate electricity decreased. In France and Germany electricity shortages arose because of increased demand and constrained supply. The unusual dry summer of 2002 in Norway also lead to a shortage of electricity at the end of that year. Chile in 2007 and 2008, New Zealand in 2008 and South Africa in 2008 and 2009, also experienced electricity shortfalls caused by a drought, fuel disruption or demand growth. There have also been power outages caused by network problems, as in Italy, where a storm affected all the country in 2003.

The most recent case was in Japan in March 2011. After an earthquake and tsunami struck the east coast, several nuclear plants and thermal power stations were closed. As a result, over 27 GW of power generating facilities

were suspended (IEEJ, 2011). The government faced the need to reduce electricity demand to avoid blackouts. In May, the government announced electricity-saving targets of 15% for most sectors (IEA, 2011).

Electricity shortages are also a growing problem in developing countries. The rise in the economic activity and the higher living standards has led to an increase in electricity demand. In China, the demand for electricity rose by 41% between the years 2000 and 2007. Despite important reforms and significant investment over the last two decades, current policies cannot sustain growing demand (IEA, 2006). In 2004, 26 out of 30 Chinese provinces experienced blackouts, which mainly affected the manufacturing sector<sup>1</sup> (Fisher-Vanden et al, 2012) and caused large economic losses. In India, to meet projected electricity demand, electricity generation capacity will need to increase from 146 GW (in 2006) to 522 in 2030 (IEA, 2007a). Although electricity consumption per capita is less than half of that in China the demand has increased at a rate of around 10% in the last years. The Indian electricity sector has been characterized by shortage and supply constraints. During the year 2010-11, electricity and peak load shortages were 8.5% and 9.8%, respectively (CEA, 2011). The difference between the required and the available electricity capacity has important effects on households and industrial sector.

The consequences of these outages are particularly important for our societies, very dependent on the availability of electricity, and may generate large economic and social costs. However, and despite this importance, there is limited information about the consequences and the economic impact of the security of electricity supply. This information is critical to respond optimally to these problems: How much should we invest to prevent outages? How should we operate our power systems to minimize them? In case there is an outage, should we interrupt supply to all sectors or regions equally?

These questions are becoming more relevant with the increased penetration of renewable energy sources. Although renewable energy reduces the dependence on imported fossil fuels and increases the diversity of electricity sources, therefore increasing energy security in the long term, the variability of electricity production makes necessary to reconsider the operation and control of the electricity system (IEA, 2007b). Wind and solar technologies depend on natural cycles and are therefore intermittent, which implies non-controllable variability and partial unpredictability (Perez-Arriaga and Batlle, 2012). Both wind and solar electricity generation are very volatile, but wind is less predictable than solar, due to the fluctuations of wind speed. Although spatial aggregation and diversity (i.e., combining solar and wind plants) can reduce the variability of electricity production, in electricity systems where the international connectivity is very narrow, as in the case of

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<sup>1</sup>The manufacturing sector accounts for 74% of total electricity consumption in China.

Spain, renewables have to be supported with backups, such as combined cycle technologies. However, it is not straightforward to determine the amount of backup capacity to be installed, nor the optimal fuel stocks.

Therefore, we consider more important than ever to quantify adequately the economic consequences of electricity interruptions, since that will allow us to achieve an optimal level of security of electricity supply. This optimal level can be achieved either by setting directly the amount of reserves, the network investments, the operating procedures, or the quality of service (such as SAIDI or SAIFI) requirements; or, by sending the right signals or incentives to the agents in the liberalized power system. In both cases, we need to know beforehand the benefits derived from having less interruptions.

The aim of this paper is to quantify the economic impact of the loss of electricity supply, focusing particularly on its physical availability. More precisely, this study analyzes the economic consequences of electricity interruptions caused by generation and resource management decisions. Following Bohi and Toman (1996), we will estimate the loss of welfare resulting from a change in the physical availability of electricity.

Several studies, which are reviewed in section 3, have already addressed this particular issue. Most of the studies are based on customer surveys (Targosz and Manson 2007, LaCommare and Eto 2006, EPRI 2001). Although customer surveys can be a good methodology to estimate power interruption costs, they present some problems. The primary problem is the time and high cost associated to the collection and analysis of the data. Besides, the results may be biased given that the provision of security of supply is typically a public good, and therefore prone to suffer from a free-riding effect. Therefore, typically customers will have an incentive to give higher values to interruption costs.

In this study we use the production function approach, following previous works such as Nooij et al (2007) and Leahy and Tol (2011). This method relates the electricity use and the value generated with it to estimate the costs of electricity interruptions. In contrast to other methods, the production function approach does not require analyzing each sector separately, and provides an objective assessment of total costs. Furthermore, it relies on available data, which facilitates the analysis.

Compared to previous literature, this paper offers a more detailed temporal, sectoral and geographical estimation of the costs of an interruption in electricity supply, and also refines the way in which assessments should be done for the different economic sectors. In particular, we estimate interruption costs excluding those sector in which electricity is not essential, and therefore, a more precise value is provided. We study the Spanish electricity system since we consider it is a very good example of a system with

a large penetration of renewables and therefore a pressing need for a good estimation of the costs of electricity interruptions.

The results obtained in this paper can be compared and also used to refine those obtained with other methods. We show the costs of electricity interruptions in different sectors, regions and years. As mentioned before, this information could be valuable for policy-makers or managers of the electricity system. From the supply side, the estimation of electricity interruption cost is useful to optimize fuel stocks, capacity reserves and investment decisions. From the demand side, it can help to assess demand-side management measures, such as demand-response programs, which try to optimize the operation of the power system.

The paper is organized as follows. Section 2 describes the Spanish electricity system. Section 3 presents the different methods employed in the literature and the empirical evidence of electricity interruption costs. In Section 4 we apply the production function approach to the Spanish economy. Finally, in Section 5 we offer some conclusions and implications for policy.

## 2 Spanish electricity system

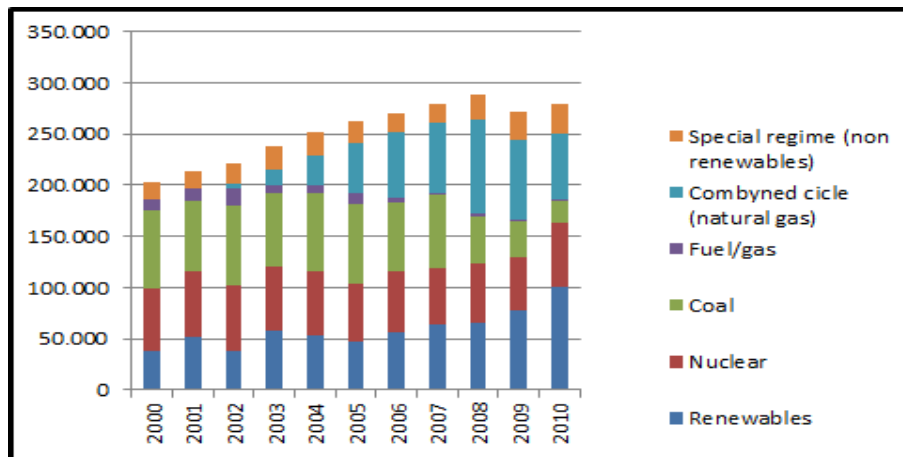
The Spanish electricity system has changed considerably in the last decade. While renewable energy sources and combined cycle (natural gas) have increased their weight in the electricity mix, coal and nuclear plants have reduced their share in the electricity production. Figure 1 shows the electricity mix in Spain from 2000 to 2010. In 2000, coal and nuclear energy together accounted for 68% of total electricity production; nowadays it is around 30%. On the other hand, in 2010 renewables and natural gas accounted for 36% and 23%, respectively.

The rise of renewable energy and combined cycle has contributed to increase the installed capacity. In 2010 the installed capacity was 99,043 MW; this implies an increase of 4.7% from previous year. Since 2006, the installed capacity of renewables (wind and solar) and combined cycle have increased by 92% and 63%, respectively.

Although the penetration of renewable energy technologies has contributed both to diversify electricity production sources and to reduce dependence on energy imports, there are still some challenges for the Spanish electricity system. First, in absence of technologies that allow energy storage and/or demand response services, renewables, at high levels of penetration, require back up capacity. Some technologies such as wind, hydro and solar, depend on natural cycles, and therefore, increase the variability of energy

production. The last report of Red Elctrica Española (REE)<sup>2</sup> shows that in 2010 electricity production from wind reached a maximum of 54% and a minimum of 1% in two different moments<sup>3</sup>. In this context, an optimal investment and management of flexible generation technologies is crucial. Second, although the share of nuclear has decreased, the total production is still high. Nuclear plants are characterized by a low flexibility and therefore cannot be used to back up renewables. Third, the electricity interconnection capacity between Spain and France accounts for only 3% of the maximum current demand on the Iberian Peninsula. This value is below the 10% interconnection capacity which the European Union established as a minimum level in the Barcelona Summit in 2002. The last potential challenge for the security of electricity supply in Spain is the growing electricity consumption. The commitment of European countries to reduce CO<sub>2</sub> emissions can lead to an electrification of the economy, especially in the transport sector. This would imply a higher electricity demand which should be met with new capacity.

Figure 1: Spanish electricity mix (GWh)



Source: Red Elctrica Española

A changing electricity system requires a careful analysis and management. The high penetration of renewable energy and natural gas in the Spanish electricity system has some advantages, but also entails some new risks. In addition to environmental and economic issues, policy-makers should take into account the security of electricity supply, and one of the key factors that

<sup>2</sup>REE (2011). REE is a Spanish company dedicated to the transmission of electricity and the operation of electricity systems.

<sup>3</sup>On 9 November at 3.35 am 54% of demand was met with wind energy, while on 26 June at 10.32 am just met 1%.

determine the security of electricity supply is interruption cost.

### 3 Methods and empirical evidence

The consequences of electricity interruptions can be classified in three categories (Tasgosz and Manson, 2008):

- Direct economic impacts:
  - Loss of production
  - Restart costs
  - Equipment damage
  - Raw material spoilage
- Indirect economic impacts:
  - The cost of income being postponed
  - The financial cost of loss of market share
- Social impacts:
  - Uncomfortable temperatures at work/home
  - Loss of leisure time
  - Risk to health and safety

An optimal analysis should capture all the impacts. However, the lack of data makes this task very difficult. Each methodology has advantages and disadvantages; some methods estimate better direct economic impacts, while other methods are able to capture indirect and social impacts. On the other hand, not all electricity interruptions have the same consequences. Social and indirect economic impacts are larger when interruptions are unexpected. Likewise long interruptions have mainly direct economic impacts. Therefore, when analyzing electricity interruptions, it is necessary to choose the methodology which better captures each impact.

In the literature, there have been different attempts to quantify electricity interruption costs. The three most common methods are:

- Customer Surveys: In this method, surveys are employed to obtain information from industrial, commercial and residential sector customers. The objective is to obtain a direct or indirect valuation of interruption costs from customers. Direct approaches are employed for



those customers with a good knowledge of interruption consequences (e.g., industrial sector and other large electrical users). Under some guidance, customers are asked to identify the impacts and evaluate the costs related an electricity interruption. When interruption impacts are less tangible and the monetary loss is more difficult to evaluate, indirect evaluation methods are employed (e.g., for the residential sector). Usually people are asked about their willingness to pay (WTP) to avoid interruptions, or their willingness to accept (WTA) a compensation for having a higher number of interruptions. As mentioned before, given that security of supply can be considered as a public good, consumers will tend to overestimate their interruption costs to free-ride on the system. On the other hand, they can also be interested in underestimating them if their contribution to paying for the cost of security of supply is higher than their share in the costs of an interruption.

- Case studies: Past events, as the blackouts occurred in California in 2001 and 2002, can be used to quantify the cost of power interruptions. The advantage of this method is that estimations are based on real events rather than hypothetical scenarios. It is easier for electricity consumers to provide a more detailed cost evaluation when they have experienced an interruption. However, this methodology is limited by the specific characteristics of the outage studied (e.g., place, time, duration); and it is difficult to generalize the results.
- The production function approach: This method uses the ratio of an economic measure (e.g., gross domestic product, gross value added) and a measure of electricity consumption (e.g., kWh) to estimate interruption costs by sector. The objective is to find the value of one unit of electricity, also known as the Value of lost load (VoLL). For example, if the gross value added of a sector is €10 million using 1 million kWh of electricity, the cost of a power interruption would be €10/kWh. Under the production function approach, it is assumed that electricity is essential for production, which is not always true. In some sectors, an electricity interruption does not necessarily imply a production break. Furthermore, production may be postponed or displaced to other locations or time slots. Therefore, this method may overestimate electricity interruption costs. It is also easy to notice that this measure of VoLL is the inverse of energy intensity, which measures the amount of energy required to produce a unit of economic output. Therefore, electricity-intensive sectors will by definition show a lower VoLL. But this does not include the dependability of the sector on electricity consumption, which may also be very relevant for the quantification of the cost of lost load.

The three methods have their advantages and disadvantages. Hence, when analyzing the costs of electricity interruptions, it is important to consider the cause and characteristics of the interruption. The production function approach can be appropriate to estimate the costs in electricity shortages as a result of a drought, nuclear crisis, etc., and also for sectors for which electricity supply is critical and production cannot be shifted. In this case, electricity interruptions are predictable and therefore, the costs are mainly production losses. Customer surveys is a better method to estimate social and indirect economic impact, and therefore, it should be employed when analyzing interruptions costs related to poor power quality and mechanical failures.

In the literature, both the production function approach and customer surveys have been employed to estimate electricity interruptions. Nooij et al. (2007) and Leahy and Tol (2011) use the production function approach to estimate the VoLL in the Netherlands and Ireland respectively. Nooij et al. (2007) find that in 2001 the cost of 1 kWh of electricity not supplied in the Netherlands was €8.56. Their results show big differences between sectors. They find that an electricity interruption would cost €33/kWh to the construction sector; while in manufacturing would be €1.87/kWh. For households, they estimate a VoLL of €16/kWh. In Ireland, Leahy and Tol (2011) find that in 2008 the cost of electricity interruptions was €12.9/kWh<sup>4</sup>. They also find that the VoLL for households (€24.6/kWh) is higher than in the industrial sector<sup>5</sup> (€4/kWh).

However, most of the studies which estimate the cost of power interruptions are based on customer surveys. In surveys, people are asked about the cost of an interruption (as a function of duration). In contrast to the production function approach, interruption costs are usually not expressed in terms of the total energy not supplied (€/kWh), but of the load disconnected (€/kW). Balducci et al (2002) use survey data collected by the University of Saskatchewan in 1992 and 1996 to estimate interruption costs in U.S. They find that in 1996 the average cost of an hour interruption in U.S. economy was \$8.76/kW. The differences among sectors are significant. Interruption costs for the transport sector are \$16.42/kW per hour, while the cost for households is \$0.15/kW. They also estimate the costs for the industrial sector (\$13.93/kW) and the commercial sector (\$12.87/kW). Billinton (2001) also uses the data collected by the University of Saskatchewan to calculate one hour interruption cost for the industrial (C\$5.19/kW) commercial (C\$32.20/kW) and residential (C\$0.31/kW) sectors in Canada.

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<sup>4</sup>The cost, in terms of 2001€, is €11.04/kWh. Therefore, the VoLL for Ireland is 30% higher than in the Netherlands.

<sup>5</sup>The construction sector is included in their industrial sector.

Table 1: Summary of Interruption Cost Studies

Author	Country	Year	Methodology	Sectors	Findings
Targosz and Manson (2007)	EU-25	2004-2006	Surveys	Industrial and services	Total Cost: €150 Billion Annually
LaCommare and Eto (2006)	US	2001	Surveys	Residential	\$ 1.5 Billion Annually
				Comercial	\$ 56.8 Billion Annually
				Industrial	\$ 20.4 Billion Annually
				Total	\$ 79 Billion Annually
EPRI (2001)	US	2001	Surveys	Digital Economy	\$ 13.5 Billion Annually
				Manufacturing	\$ 3 Billion Annually
				Services	\$ 29.2 Billion Annually
Nooij et al (2006)	Netherlands	2001	Production Function	Agriculture	€3.90/KWh
				Manufacturing	€3.90/KWh
				Construction	€33.05/KWh
				Transport	€12.42/KWh
				Services	€7.94/KWh
				Government	€33.50/KWh
				Households	€16.38/KWh
				Total	€8.56/KWh
Leahy and Tol (2010)	Ireland	2007	Production Function	Industrial	€4/KWh
				Commercial	€14/KWh
				Households	€24.6/KWh
				Total	€12.9/KWh
Balducci et al (2002)	US	1996	Surveys	Industrial	\$ 13.93/kW (1 hour interruption)
				Commercial	\$ 12.87/kW (1 hour interruption)
				Households	\$ 0.15/kW (1 hour interruption)
				Transport	\$ 16.42/kW (1 hour interruption)
				Total	\$ 8.76/kW (1 hour interruption)
Billinton (2001)	Canada	1996	Surveys	Industrial	C\$ 5.19/kW (1 hour interruption)
				Commercial	\$ 5.88/kW (1 hour interruption)
				Households	\$ 0.31/kW (1 hour interruption)
Trengereid (2003)	Norway	2001-2002	Surveys	Industrial	€8.5/KWh
				Services	€12.7/KWh
				Agriculture	€1.3/KWh
				Households	€1.0/KWh
				Public service	€1.7/KWh
Bertazzi et al(2005)	Italy	2003	Surveys	Business	€21.6/KWh
				Households	€10.8/KWh

Surveys have also been used to estimate interruption costs in some European countries. Trengereid (2003) estimate interruption costs in Norway both when electricity interruption is notified and when it is not. The agricultural, residential and public sectors do not show significant cost differences when the interruption is notified. On the other hand, the cost for industrial and commercial sector increases around 45% when the interruption is not notified. Bertazzi et al (2005) estimate electricity interruption costs for Italy. They find that the cost for business sector (industrial, services, agricultural and public sectors) is €21.6/kWh and for households is €10.8/kWh.

As mentioned before, one possible use of these estimates would be the adequate definition of incentives for quality of service (such as SAIDI or SAIFI), such as in Growitsch et al (2010). Uluski (2007) and Bouhouras et al (2009) use electricity interruption costs to assess the benefits of Distribution Automation and Artificial Intelligence Systems in distribution networks, respectively.

The results obtained from surveys differ from those obtained under a production function approach in two important aspects. First, the cost of power interruptions for households is relatively higher under the production function approach, which considers the loss of leisure time as an indicator of this cost. Surveys instead result in households being among the sectors with lower values. This might be explained, following an idea presented earlier, by the significant substitutability in household activities: instead of watching television one can read a book. That is, when activities may be shifted in time, the production function will overestimate the damage of an electricity interruption. However, surveys also show weaknesses in order to estimate power interruption costs in households. People are usually asked about how much they are willing to pay to avoid interruptions. Besides of the biases already mentioned, people may underestimate the cost because they are not used to electricity interruptions and view electricity supply almost as a social right. Indeed, this is consistent with the fact that people (and policy-makers) try very hard to keep electricity prices low, in spite of the large utility it provides.

The second important difference between the results of both methodologies lies in the electricity interruption cost for the industrial sector. Surveys show that one hour interruption causes similar damage (as a function of load disconnected) in the commercial and the industrial sector. However, the studies which use the production function approach find that the cost of 1 kWh not supplied in the service sector is around 4 times higher than in the industrial sector. The difference could be explained by the fact that indirect impacts of electricity interruptions are higher in the industrial sector, and these are not captured with the production function approach. This problem could be partially solved using input/output tables, which show

the interdependencies between sectors. The slowdown in industrial activity may affect other sectors which depend on industrial supplies, and therefore, an electricity interruption in the industry would affect indirectly other sectors. Another explanation could be that electricity supply is less critical for services than for the industrial sector, although the latter are more electricity-intensive (and therefore value added per kWh will be lower). That is, although the value added per kWh in services may be higher, the consequences of an electricity shortfall may be easier to avoid when electricity is not central to the production/service process.

Despite the differences in the results, both the production function approach and surveys provide useful information to policy-makers. The production function approach is a good method to account for production losses when they cannot be avoided by shifting production to other time, and also when electricity is critical for production. Surveys can be employed to complement this information. In some sectors, such as the industrial one, indirect and social impacts are very important, and thus, surveys can be used to capture these costs.

## 4 The production function approach: an application to Spain

In this paper, we use the production function approach to estimate the economic impact of electricity interruptions in Spain. In absence of survey data, this method allows us to use available data to estimate interruption costs for any sector. The results obtained in this paper could be complemented and refined with those obtained with other methods.

The production function approach employs slightly different techniques to calculate the costs for firms (and the government) and households. In both cases, the objective is to use available data<sup>6</sup> to find the value of lost load (VoLL), that is, the value created by one unit of electricity.

In the case of firms and the government, we assume that electricity is essential for its activity. Thus, electricity interruptions imply that production process must be stopped, regardless of the sector<sup>7</sup>. Firm losses are quantified as the Gross Value Added not generated in that period. Therefore, the VoLL (€/kWh) is obtained by dividing the GVA (€millions) by the amount of electricity used (GWh). Notice that the production function

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<sup>6</sup>The data employed in this analysis is taken from Eurostat, INE and REE.

<sup>7</sup>It is assumed that no other productive activity is possible during a power interruption, which may not be true in some cases, and therefore, the costs might be overestimated for some sectors.

approach only considers production losses; other impacts such as equipment damage or raw material spoilage are not quantified. As mentioned before, the method assumes that the production process cannot be shifted to other time slots. This can be true in a fully-employed economy, but not necessarily when there is spare capacity.

In the case of households, it is assumed that electricity is essential for some leisure activities. Consequently, in absence of electricity, leisure time is lost. The Spanish National Statistics Institute (INE) provides information on the distribution of activities in an average day (Time use survey 2009-2010). Table 2 shows the time that the average Spanish person spends on the major leisure activities. This information allows us to estimate the amount of time spent on leisure. We assume that domestic activities, computer activities, watching TV, listening to the radio and social activities require electricity, and therefore, the time employed in these activities is lost when there is an electricity interruption. Again, the same caveat about the substitutability of these activities applies.

Table 2: Activities per day in hours (2009)

	Hours	Minutes
Personal care	11	30
Paid work	2	28
Education	0	39
Domestic activities and family	3	2
Voluntary work	0	14
Social activities	1	3
Sports	0	44
Computer activities	0	34
Tv, video, radio, reading	2	37
Travel other	1	10

Source: INE

To monetize leisure time, we assume that the value of one hour of leisure time equals the income per hour; i.e., the net hourly wage<sup>8</sup>. In 2008, the average gross hourly wage was €13.53 in Spain. As in Nooij et al (2007), we assume that opportunity cost of leisure for inactive and unemployed people is lower, and therefore, one hour of leisure time is equal to half of the average wage<sup>9</sup>.

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<sup>8</sup>This assumption is commonly used in economics. Becker (1965) states that a marginal hour of leisure time equals the income per hour.

<sup>9</sup>Nowadays, given that the unemployed rate in Spain is above 20%, this value could easily be an overestimation.

As mentioned before, the cost of power interruptions for households might be overestimated if, during an interruption, people are able to spend their leisure time in other activities that do not require electricity. However, on the other hand, we do not quantify other costs such as food spoilage and personal damages, which would increase the costs.

As we have explained previously, the production function approach employs the Gross Value Added (GVA)<sup>10</sup> and the electricity use to calculate the cost of one unit of electricity not supplied (VoLL). Table 3 shows the results for the Spanish economy in 2008. Services are the most important economic sector in terms of the GVA; it accounts for 50% of economic activity. However when we consider the value of leisure time, households become the main sector in terms of GVA; they represent the 39% of total GVA. This is consistent with the general idea that electricity has a large utility and a very low price elasticity for households, which in turn results in higher prices compared to other sectors.

The contribution of other sectors, such as manufacturing, construction and the government, is 7.8%, 7.4% and 11% respectively. The electricity use is not proportional to the GVA. Manufacturing uses 33.6% of total electricity, while it creates less than 10% of total value. On the other hand, services create 31.4% of the value using 22.2% of the electricity. This basically reflects the nature of these productive processes, or their electricity intensity.

In the last column of Table 3, it is shown the value of lost load (VoLL), which is obtained dividing the GVA by the electricity use. The VoLL can be understood as the value created with 1 kWh of electricity. The results show that, including all sectors, Spain generates €5.98 with 1 kWh of electricity. However, there are big differences between sectors. The construction sector has the highest VoLL (€33.37/kWh). The VoLL for households, services and transport is very similar; they create around €8 with 1 kWh of electricity. Manufacturing has the lowest VoLL (€1.5/kWh). In this sector, transport equipment is the industry that generates more value with one unit of electricity (€3.8/kWh), while metal industry generates €0.90/kWh.

However, it is difficult to defend that electricity interruptions have a higher economic cost in, e.g., the construction sector than in some industrial sectors. This is because electricity is essential for some activities such as textiles and, on the other hand, construction can be active without electricity. Hence, and as a contribution compared to previous exercises, we divide Table 3 in two categories, those sectors where electricity is essential and those sectors where it is not essential. In this way, we can focus on those sectors where electricity is an essential input, and compare the economic effects of electricity interruptions. When we exclude those sectors for

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<sup>10</sup>For households, the GVA is the value of leisure time.

Table 3: Electricity use, GVA and VoLL in Spain (2008)

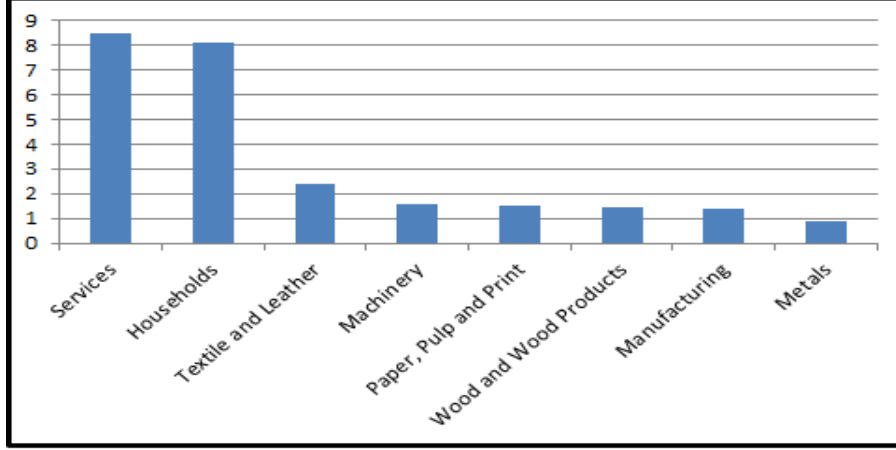
	Electricity Use (GWh)		GVA (€millions)		VoLL (€/KWh)
Agriculture	6028	2.36%	26494	1.73%	4.40
Manufacturing	85974	33.60%	118796	7.76%	1.38
Metals	28677	11.21%	25763	1.68%	0.90
Chemical	11587	4.53%	13907	0.91%	1.20
Non-Metallic	11147	4.36%	11420	0.75%	1.02
Food	10973	4.29%	20245	1.32%	1.84
Textile	2635	1.03%	6377	0.42%	2.42
Paper	8058	3.15%	12332	0.81%	1.53
Transport	3834	1.50%	14579	0.95%	3.80
Machinery	6897	2.70%	10997	0.72%	1.59
Wood	2166	0.85%	3176	0.21%	1.47
Construction	3402	1.33%	113511	7.42%	33.37
Transport	3287	1.28%	28037	1.83%	8.53
Services	56786	22.19%	480718	31.42%	8.47
Government	27246	10.65%	169639	11.09%	6.23
Total (exc. Households)	182723	71.41%	937195	61.25%	5.13
Households	73149	28.59%	592908	38.75%	8.11
Total	255872	100%	1530103	100%	5.98

which electricity is not essential, the figure increases a bit, to €6.35/kWh. The reason is that, although we are excluding the construction sector, we are also excluding other sectors with a very low cost and still keeping the commercial and residential sector, for which interruption costs are relatively high.

Figure 2 shows the VoLL in those sectors where electricity is essential. Services and households are the sectors where electricity interruptions have a higher cost. These sectors represent the second and third larger electricity consumers in Spain, and generate around one third of the value each. The cost of an interruption for services and households would be around €8/kWh. For other sectors where electricity is essential, the VoLL is much lower. For instance, in the metal sector, one of the most important electricity consumers (11% of total consumption), the GVA generated with 1 kWh is less than €1. Remember that we only account for production costs, and therefore, the total cost may be higher. This is especially true in the industrial sector, where there may be additional costs related to equipment damage and start-up costs. Furthermore, these latter costs are fixed, independently of the length of the interruption, and therefore, a short interruption may cause higher costs in the industrial sector than in the rest of the sectors. Again, these results are consistent with the typically higher elasticities for industrial sectors.



Figure 2: VoLL in Sectors where electricity is essential



Compared with other studies, our results show that the VoLL in Spain is lower than in the Netherlands and Ireland. Nooij et al. (2007) find that in 2001 the VoLL in the Netherlands was €8.56/kWh (€9.92/kWh in terms of 2008€) and Leahy and Tol (2011) also find a higher VoLL for Ireland, €12.9/kWh in 2008.

This can be explained by the differences in energy intensity in Spain. Indeed, those sectors in which the difference in energy intensity compared to EU countries is larger (e.g. households) show also larger differences in terms of VoLL: in the Netherlands the cost of an electricity interruption for households is €16.38/kWh (€18.98/kWh in terms of 2008€) and in Ireland €24.6/kWh, while in Spain the cost is €8.11/kWh. This difference cannot be explained by a higher electricity consumption of Spanish households<sup>11</sup>, and therefore, it may be due to a lower average gross wage in Spain, which leads to a lower value of leisure time<sup>12</sup>.

In turn, differences are not large when we exclude households: the VoLL in Spain is €5.13, while in the Netherlands is €5.97/kWh (€6.92/kWh in terms of 2008€).

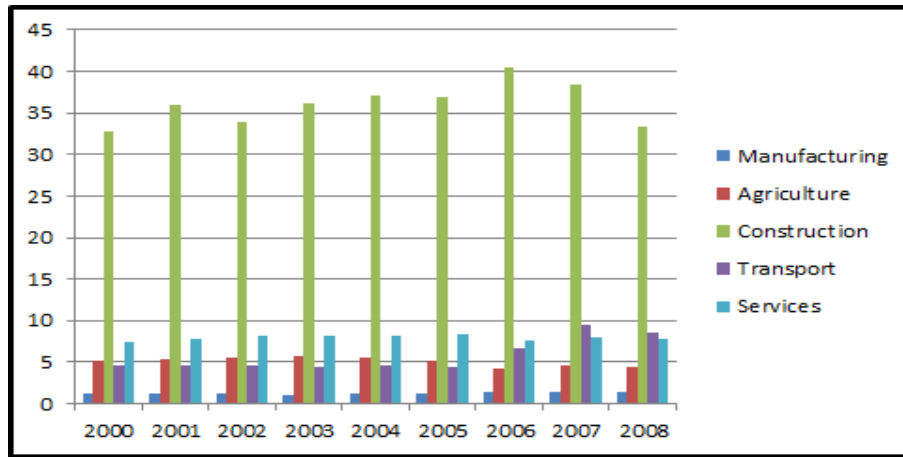
It is also interesting to look at the temporal evolution of these values. Fig. 3 shows the evolution of the cost of electricity interruptions between

<sup>11</sup>According to Eurostat, in 2008, the electricity consumption per capita in the residential sector was 1.61 MWh in Spain, 1.51 MWh in the Netherlands and 1.94 MWh in Ireland.

<sup>12</sup>In 2001 the average gross wage in the Netherlands was €18.65 (€21.61 in terms of 2008€), while in Spain, in 2008, it was €13.53.

2000 and 2008<sup>13</sup>. The cost of 1 kWh of electricity not supplied has declined in most of the sectors. This is consistent with aggregate values<sup>14</sup>. During these years electricity consumption (excluding residential consumption) increased 35% and GVA only 27%. Despite the housing boom, the largest decline has been in the construction sector. This is because the electricity use in that sector has more than doubled, while the GVA has increased 40%. There has also been a decline in services (including the government), due to the rise in electricity use. Between 2000 and 2008 the VoLL in this sector has decreased from €9.65/kWh to €7.74/kWh. In manufacturing the cost of electricity interruption has remained fairly constant and in the transport sector has increased.

Figure 3: The VoLL between 2000 and 2008(€/kWh)



The value of the lost load also changes throughout the day: neither economic activity nor electricity consumption are constant in this period. Thus, the cost of an electricity interruption varies depending on the time of day. We use estimates of hourly electricity consumption from Red Eléctrica Española (REE) to calculate the average value of an hour without electricity in the commercial, industrial and residential sector. To obtain the average value of a lost hour we multiply hourly electricity consumption<sup>15</sup> by the value of one unit of electricity (VoLL) in each sector.

<sup>13</sup>The costs are shown in terms of 2008. In the Appendix we show a table with the values.

<sup>14</sup>The statistics of the Spanish Institute for Energy Diversification and Saving (IDAE) show that electricity intensity increased 12% and 9% in services and industry, respectively, between 2000 and 2008.

<sup>15</sup>Consumption estimates refer to an average winter day.

Fig. 4a shows the results for services. Economic activity is concentrated during standard business hours in this sector. The cost of one hour electricity interruption increases during the morning, and at midday reaches the highest value (€118 million). There is a decrease of the activity during lunch time, and at 6 p.m. there is a second peak. During the night, the cost of an interruption is around €50 million.

Industry is the sector with the highest electricity consumption. However, it is the sector with the lowest VoLL, and thus, one hour electricity interruption is not as costly as in services (again, assuming that production cannot be shifted in either of them). Fig. 4b shows the average value of a lost hour of electricity in this sector. Activity does not decrease during the night, and therefore, the cost of an interruption remains constant all day; around €18 million.

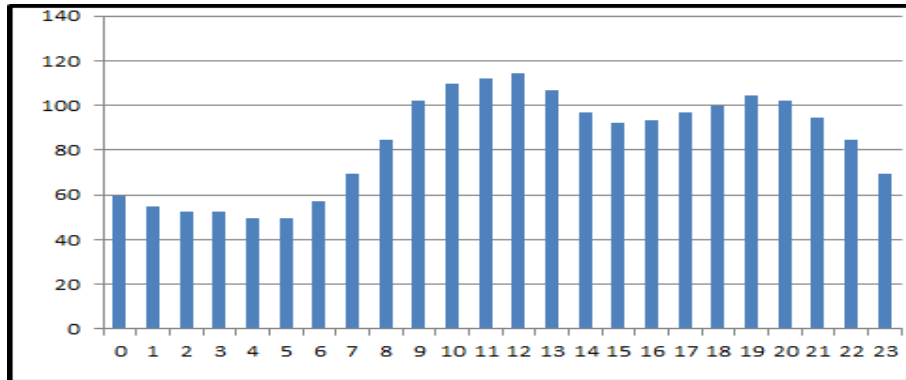
Fig. 4c shows the cost of one hour electricity interruption for households. The cost increases throughout the day and reaches a peak at lunch time. At 6 p.m., when people go back home from work, residential electricity consumption increases. The second peak is at 10 p.m., when most of the people are at home. The cost of one hour interruption at that moment is around €80 million.

The variability of electricity interruption costs throughout the day has important policy and system operation implications. During standard business hours, most of the Spanish GVA is generated in the service sector, and therefore, electricity interruptions should be avoided in this sector. During the evening, most of the people are at home, and electricity interruptions affect the residential sector particularly. The high activity of the industrial sector during the night makes this sector more vulnerable to electricity interruptions from 1 a.m. to 6 a.m.

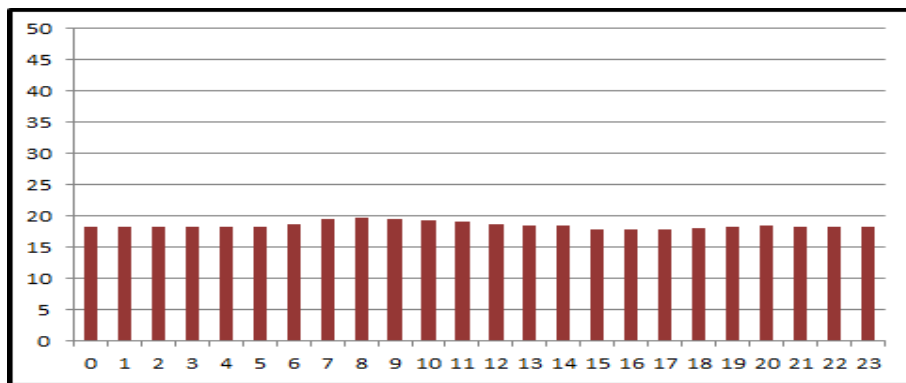
These results can also be obtained at the regional level. Indeed, Spanish economy is very heterogeneous. Southern Spain is characterized by tourism-oriented economy, and therefore the contribution of services to GVA is very high. In northern Spain, although services are the main economic activity, industry has a greater weight on GDP than in the south. This implies differences on the cost of electricity interruptions.

Figure 4: The average value of a lost hour of electricity (€millions)

(a) services



(b) industry



(c) households

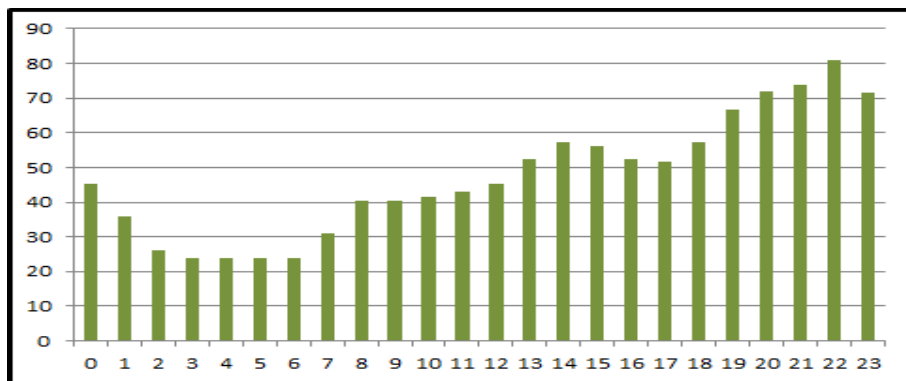
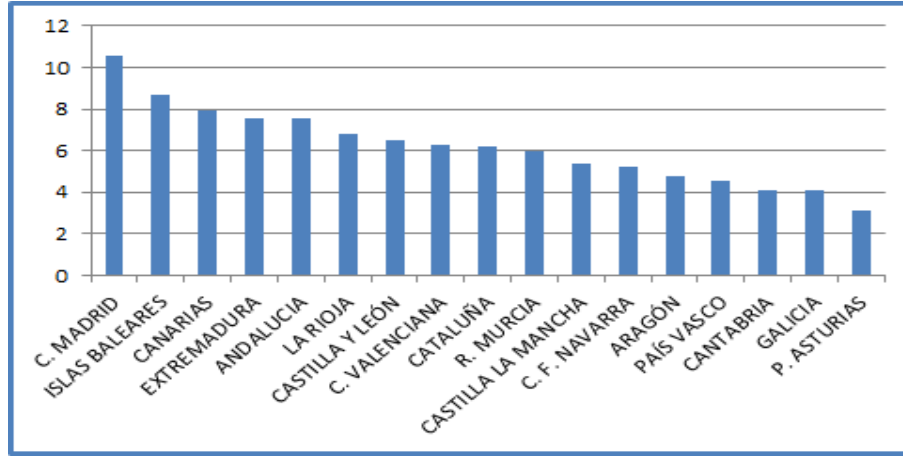


Figure 5 shows the VoLL for all Spanish regions<sup>16</sup>. Madrid, Balearic and Canary Islands are the regions with the highest VoLL; the economic cost of 1 kWh of electricity not supplied in Madrid is above €10. The economic activity in Balearic and Canary Islands is mainly based on tourism, and therefore services represent around 65% of the GVA. In these regions, like Madrid, the higher contribution of services to the GVA leads to a higher VoLL on average. On the other hand, the VoLL in Asturias, Cantabria and Galicia is the lowest. The higher contribution of the industry to the GVA in these regions explains a lower VoLL. The VoLL in Asturias is €3.12/kWh; thus, the economic effects of an electricity interruption in Madrid are three times higher than in Asturias.

Figure 5: Total VoLL in Spanish regions (€/KWh)



In Table 4, we show the VoLL of each economic activity in all regions. The economic effects of power interruptions in a given sector are very different depending on the region. The differences in the service and public administration sector can be explained by the higher productivity in regions such as Madrid, the Basque Country and Navarra. The VoLL in services varies from €14.92/kWh in the Basque Country to €8.85/kWh in Balearic Islands. Industry also shows big differences. This can be due to the weight of each subsector on the industrial sector. For instance, the VoLL is lower in the iron and steel industry, which is mainly present in the North of Spain. Hence, we observe that the VoLL in Asturias is €0.7/kWh while in Madrid it is €4.57/kWh.

<sup>16</sup>For the regional analysis we have excluded households.

Table 4: VoLL (€/KWh) in Spanish Regions (2008)

	AND	AR	CAN	CAB	CM	CL	CAT	MAD	NAV	VAL	EXT	GAL	IB	LR	PV	AST	MUR
Agriculture	4.04	5.16	1.82	10.6	3.60	6.76	6.11	4.09	4.74	3.17	6.60	16.3	2.91	11.5	13.1	18.7	1.40
Industry	1.92	1.41	4.56	0.97	1.85	1.89	2.16	4.57	1.78	2.17	1.24	0.89	6.44	2.65	1.42	0.70	2.47
Construction	43.7	75.9	50.1	49.9	23.0	28.2	49.2	24.1	27.7	23.8	102.9	31.5	34.0	45.3	41.2	38.6	17.4
Services	11.1	10.4	9.4	12.7	8.57	13.1	10.5	13.7	13.6	10.0	14.6	12.3	8.85	11.4	14.9	11.4	10.7
Government	8.38	8.58	5.18	7.69	6.27	8.53	7.94	8.07	10.5	6.70	9.64	8.50	6.88	8.18	11.1	8.62	6.73
Total	7.52	4.79	7.95	4.14	5.35	6.53	6.21	10.55	5.22	6.31	7.59	4.12	8.65	6.83	4.57	3.12	6.01

## 5 Conclusion

The correct determination of the economic impact of electricity interruptions is critical for the achievement of the optimal levels of security of supply in the electricity sector. In particular, knowing the economic damage that an interruption may create allows to send the right signals to the agents in the power system, and to determine the right levels of reserves, quality of supply, or investments in networks. This is even more relevant in countries like Spain with a significant penetration of intermittent renewable sources.

In this paper we attempt to contribute to this determination by estimating the production losses resulting from an electricity interruption in Spain. We employ the production function approach for this analysis, although it has some limitations: this method only captures production losses and is not able to quantify social and indirect economic impacts. In addition, it assumes that the production activity cannot be shifted to other periods and therefore is lost. It does not consider either the criticality of the supply of electricity for each specific production activity.

However, and absent data from other approaches (such as surveys), we still think that this method can provide a suitable approximation to estimate costs in electricity shortages when the interruption is notified, and therefore, social and indirect economic impacts are smaller; or when there is no possibility to shift production in time. Therefore, we think that it can be considered as a good starting point to estimate interruption costs in Spain. The methodology employed in our analysis is not incompatible with other methods, and therefore, the results are open to improvement. Surveys could be used to quantify social and indirect economic impacts of electricity interruptions.

We find that the cost of one kWh of electricity not supplied in Spain is

€6.35 (€5.98 if we include those sectors where electricity is not essential). However, there are large differences between sectors and regions. For example, the damage of one unit of electricity not supplied to the commercial or households sector is higher than the damage for manufacturing<sup>17</sup>. In addition, these differences vary throughout the day. The activity of the service sector is concentrated in the standard business hours, and therefore, the cost of one hour of electricity interruption is higher at that moment. During the night, the industrial sector does not decrease the activity, and consequently, the cost of electricity interruptions is relatively higher in this sector.

The heterogeneity of Spanish economy also makes electricity interruption costs vary between regions. In Spanish regions where the importance of the service sector is higher, the VoLL is also higher. Thus, the VoLL in Madrid, Balearic and Canary Islands are around twice that in Asturias, Cantabria and Galicia.

The absolute level of the cost of the interruption, and also its temporal, sectoral and geographical has important implications for policy makers or regulators. Indeed, as mentioned before, these values should be taken into account when deciding the level of investments on network or backup reserves, or when sending signals to the power system agents.

Regarding the absolute level: most of the current signals sent to the Spanish power system are considerably lower, whereas some are clearly excessive. For example, the price cap in the wholesale electricity market is €0.18/kWh; the cost of non-supplied energy in many modeling exercises is also lower than €0.3/kWh. The incentive for quality of service for distribution companies is also lower (around €1/kWh) than the cost estimated.

On the other hand, there are also examples where the incentive is clearly overestimated. For example, the rebate offered to industries for being available for an interruption (the interruptibility cost, as it is termed) is in average €140/kW, which is clearly higher than the cost avoided by this service.

Moreover, these signals do not vary with the sector, region or time of the day, whereas the economic cost of interruptions do.

Therefore, at least for Spain, it seems that current regulations regarding security of electricity supply do not account correctly for the cost of interruptions. This has been already pointed out by Lopez Milla (2006) and Blazquez-Gomez and Grifell-Tatje (2011), who argue that the legislative changes introduced in 1998 for the reimbursement of electricity distribution companies do not provide incentives for efficient investment and manage-

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<sup>17</sup>Although the highest cost belongs to the construction sector, we do not consider it here because electricity is not that critical and therefore would imply overestimating the cost.

ment decisions. This basically means that the level of security of electricity supply in Spain, derived from these incentives is not optimal, since the incentives for achieving it are either much lower, or, in some cases, higher, than the benefits to be obtained.

The costs estimated in this paper, which should be refined and complemented with further research, could constitute a first step towards correcting this situation, which is preventing the achievement of an optimal level of security of electricity supply in Spain.



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## Appendix

Table 5: The VoLL in Spain from 2000 to 2008

	2000	2001	2002	2003	2004	2005	2006	2007	2008
Manufacturing	1.51	1.43	1.39	1.33	1.30	1.27	1.39	1.36	1.38
Metals	0.94	0.92	0.92	0.89	0.87	0.87	0.97	0.94	0.90
Chemical	0.99	1.08	1.11	1.06	1.03	1.02	1.03	1.11	1.20
Non-Metallic Minerals	1.07	1.01	1.01	0.92	0.94	0.93	1.02	0.96	1.02
Food and Tobacco	2.11	2.20	2.04	1.92	1.80	1.77	1.87	1.85	1.84
Textile and Leather	2.07	2.04	1.79	1.81	1.71	1.63	2.29	2.12	2.42
Paper, Pulp and Print	3.03	1.73	1.74	1.65	1.61	1.67	1.74	1.59	1.53
Transport Equipment	3.41	3.76	3.73	3.63	3.38	3.23	3.85	3.91	3.80
Machinery	1.65	1.55	1.51	1.46	1.50	1.42	1.63	1.56	1.59
Wood and Wood Products	2.07	1.77	1.59	1.20	1.29	1.27	1.46	1.42	1.47
Agriculture	5.43	5.15	5.37	5.27	5.01	4.51	4.18	4.50	4.40
Construction	53.47	54.90	48.70	48.19	45.16	40.66	41.68	38.58	33.37
Transport	5.41	5.14	5.00	4.75	4.81	4.77	6.70	9.60	8.53
Services	9.65	9.74	9.68	9.28	9.10	9.05	7.93	8.20	7.74