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Studies in environmental, production and transport economics

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If your heart is a volcano, how shall you expect flowers to bloom?

Khalil Gibran

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This work is the result of almost a decade of discontinuous reflections on energy and environmental issues, trying to be(come) an environmental economist, while being a father in a crowded and ageing city, trying to survive on a bicycle!

A special mention goes to my family. Ma, pa, you gave immense love and support to this "ragazzaccio". Riccardo, Valentina thank you brother and sister for feeding my sometime discouraged spirit.

I dedicate this Phd to Tais, Leo and Elisa, my angels.

Summary

This PhD thesis uses statistics and econometric modelling to explore in empirical terms three energy and environmental economics issues.

In the first study I approach the energy-economy connection in a broad perspective employing energy, population and income data for 133 countries over four decades, to provide a graphical examination of energy intensity. Combining static and dynamic analyses, I assess the usefulness of this popular indicator, so as to unveil long term patterns characterizing energy and GDP data.

The second study enters into production. With a focus on inputs, I investigate capital/energy substitutability by estimating the production function of the manufacturing sector for seven OECD countries. Using a four-input translog specification, input substitution is quantified by the cross-price elasticity of substitution. This traditional economics treatment provides figures about the technological limits in which economic systems have to operate during times of energy scarcity, environmental constraints and resource price volatility.

The last chapter concerns an urgent issue for both human health and the environment: the ever-increasing road vehicle emissions. After estimating consumer demand for both traditional and cleaner fuels, like LPG and methane, I simulate the effects of the introducing a carbon tax in Italy on both fuel/vehicle choice and emissions.

All the studies use original and verifiable data and calculation procedures, to contribute to relevant and new insights.

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1. Introduction

Two founding contributions of ecological economics motivate the research reported in this thesis: *The Entropy Law and The Economic Process* by Nicholas Georgescu-Roegen (1971) and *The Limits to Growth* report to the club of Rome by Meadows et al. (1972). The first introduced the biophysical representation of the economic process, presenting a criticism of, and alternative to, the "mechanistic epistemology" of traditional economics. Pessimistic forecasts of the consequences of material resource use and environmental pollution for the global economic system shown in the second book casted early doubts on the growth paradigm. Shortly afterwards, neoclassical economists produced various defensive responses which suggested that one might be more positive about sustainable growth if due attention were given to price mechanisms relieving scarcity through stimulating substitution and innovation (e.g., Nordhaus, 1973; Dasgupta and Heal, 1974; and Solow, 1974). The debate, sometimes simplified as a confrontation between "neo-malthusians" and "cornucopians", is ongoing today, reinforced by global environmental challenges like biodiversity loss and climate change. Within economics, the issues raised by *The Entropy Law* and *Limits to Growth* concern the broad question of the "flexibility" of the economic system to deal with limited fossil energy and mineral resources as well as environmental challenges, triggered by growth of population, consumption and transport.

A rare example of a direct confrontation between mainstream and ecological economics views on growth-versus-environment can be found in a special section of the journal *Ecological Economics* (1997, vol. 22) dedicated to the work of Georgescu-Roegen. Here, traditional growth economists like Solow and Stiglitz debated with ecological economist Daly whether natural resources provide a limit to growth and to what extent man-made capital can substitute for non-renewable energy. This debate enlightened the concept of sustainable production on the basis of the substitutability between inputs in the production function. In particular, the issue of substitution (or complementarity) between capital and energy - or, more generally, natural resources - was the focus of the debate between the two schools of economic thought.

My interest lies on the role energy has in generating output. Within this research line, I decided to look at the energy/GDP relation. The correlation between GDP and energy has been highlighted by, among others, Kaufmann (1992), Stern (2000) and Coers and Sanders (2013), who stress the role of energy in ensuring continuous GDP growth. In the first study, I analyse the ratio between energy and GDP, also referred to as energy intensity indicator, using graphical tools. As the energy intensity has long served as an indicator of countries' sustainability, I investigate whether it is meaningful to use national energy intensity *per se* to characterize a country's economy. For this purpose, I examine the semantic quality of this indicator to judge how well it captures changes occurring to the two variables composing it. I challenge the usefulness of this indicator on the basis of the fact that the two variables are strongly correlated when considered at the level of the whole economy. This, though, hides the differences in the factors at a disaggregate level. The energy intensity study presented in Chapter 2 assembles a large database consisting of per capita energy consumption and real GDP for 133 countries over the period 1960 - 2009.

Bringing the analysis from the whole economy to the manufacturing sector, Chapter 3 addresses an important research question: the role that energy and materials play in the production function. I develop an econometric model for France, Germany, Italy, Japan, Spain, the UK and the USA to derive an updated, original estimate of the elasticity of substitution between capital and energy. The task involved combining insights from quantitative energy economics and ecological economics to understand how output, capital, raw materials and energy are connected.

In addition to a macro-level analysis, a sub-national sectoral angle is adopted in the research presented in Chapter 4. The urge to diversify energy sources in the transport sector and to protect the climate provides a strong momentum to assess the potential of alternative fuels vis-à-vis conventional ones. Choosing a highly-motorized country, Italy, whose transport-related emissions have increased in the last years, I consider to what extent carbon taxation can stimulate a shift from gasoline and diesel consumption to low-carbon fuels, LPG and methane. For this purpose, I use an original detailed data set, and develop an econometric model to study the extent of fuel-shifting from carbon taxation. An additional motivation for this study is that, globally, transportation has been the main economic sector showing an increasing trend of CO_2 emissions over the 1990-2013 timeframe (World Bank 2016).

2. Can we use national Energy Intensity as an indicator for decoupling?[1]

2.1 Introduction

Energy intensity (EI) is a popular indicator among researcher as it synthesises in a single number how much energy is needed at the factory, sector or country level, to produce a monetary unit of output. In particular, the declining trend of EI in advanced economies has been regarded as a positive indicator of "greener" production performance: a lowering EI over time supports the concept of decoupling between economic output and emissions.

My original idea was to compare the EI of different countries in a given year on a plane to visualise the inputs (energy and GPD) on the two axes: I "open" the EI. By doing so it appears clearly how the ratio actually hides the fundamental information to characterize an economy. Observing how totally different countries share the same EI, I perform a cluster analysis assembling as many countries and years as possible. The long-term evolution of EI in 130 countries over 50 years is studied by gathering official UN, IEA and World Bank data sources on prices, income, energy consumption and population, resulting in a dataset available for further research. This extensive information on EI is used in two ways:

i) a static analysis to map world countries' EI in three clusters for low, medium, and high EI, for a given year (2009);

ii) a dynamic analysis where EI over time can be seen in a four dimensions animated graphs. Both in cross-country analysis and time series, the decrease in EI observed in advanced, service-based economies has often been interpreted as positive step towards sustainability, while critics point at externalisation of pollution through manufacturing industries moving to developing countries.

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[1] This chapter was published as Fiorito, G. (2013). Can we use the energy intensity indicator to study "decoupling" in modern economies? *Journal of Cleaner Production* 47: 465–473.

In the static analysis I perform a consistency-check of previous EI estimates, via multi-country representation, finding that very different countries belong to the same cluster because of the nature of the ratio making the EI indicator, i.e. the slope given by the unit MJ/$. So the further question my article asks is: *Given that Angola and Japan have the same EI, what does EI (really) means?* The results show how very different countries in terms of population, wealth and general level of development belong to the same cluster, thus invalidating the usefulness of the EI indicator at the national level.

The dynamic analysis, used to visualize the evolution in time of EI shows how there is no common trend determined by technological progress in the EI trajectory. Since approximately year 2000, the video shows two phenomena: i) major Asian countries (e.g. China and India), increase their energy use per capita (as well as EI), corresponding with export rise; ii) OECD countries reduce their energy use per capita (and EI), when starting to import energy intensive products from the former. Small rich Middle East countries, where little population benefits from major energy exports and where small changes in the ratio between export and internal use determine big “jumps” in the position over the graph, are - obviously - the most erratic.

Some evident drawbacks emerge from the (national) hierarchical level adopted in the attempt to compress into a single number the information referring to different dimensions of analysis, i.e. the economic dimension referring the added value flows and the biophysical dimension studying the energy flows as noticed, e.g. by Smil (2003) and Giampietro et al. (2011). This unconventional visual analysis provides a friendly view of the EI in most world countries over time in a 4 dimension animated graph, available online, showing the economic fundamentals of each country in terms of energy, income and population.

2.2 The popularity of the “energy intensity indicator” in sustainability analysis and the reasons for concern

2.2.1 Energy intensity as a tool to study sustainability

The Economic Energy intensity (EI) of an economy, defined as the energy needed to produce one unit of gross domestic product, is generally expressed as the ratio between primary energy consumption (e.g. tons of oil equivalent or MJ of Gross Energy Requirement) and the GDP (e.g. international - purchasing power parity - real dollars). The EI indicator is widely-adopted to assess both economic and sustainability performance of countries despite the existing criticism about the validity of such an indicator.

In relation to the energetic assessment, in the 70s and 80s many studies pointed out that differences in the quality of the mix of Primary Energy Sources (PES) and in the mix of Energy Carriers (EC) used in an economy can explain the differences in the value of EI (for an overview see Cleveland et al. 1984; Hall et al. 1986; Ayres et al. 2003; Ayres and Warr, 2005). More recent research by Duro and Padilla (2011) pointed to the role played by the mix of energy transformations and consumption structures to explain differences in EI across countries. In relation to the economic assessment Smil (2003) demonstrated that large inter-country differences in EI tend to disappear when output is measured on a purchasing-power-parity basis. In conclusion, according to Liddle (2010) four main factors explain EI differences across countries: economic structure (energy-intensive industries share in total output), sectoral composition of energy use (shares of different end-uses like industry, buildings, and transport), fuel mix and efficiency in the end-use energy conversion. For this reason, the study of EI requires a more elaborated analysis making the distinction between goods imported-dominated and non-goods imported-dominated countries. However, in spite of this solid warning about the weakness of the EI indicator to study the effect of technological changes in the economy on its efficiency (defined as the consumption of primary energy per unit of added value), this indicator is still used in studies looking for proofs of "dematerialization" or "decoupling" due to technological progress (Goldemberg and Siqueira Prado 2011, UNEP 2011).

This paper does not want to get into a theoretical discussion over the validity of this indicator as done in the literature briefly mentioned before. This paper wants simply to carry out a semantic check on the usefulness of the resulting assessments. That is, when adopting values of the EI indicator can we identify something in common among countries expressing similar values of EI? If we look at the big picture coming out from the use of this indicator over a large group of countries and a long period of time can we find some useful application? Put it in another way, without getting into a formal analysis of the factors determining the quantitative assessment, this paper wants to investigate using an empirical check whether the information provided by this indicator can be trusted as useful for sustainability analysis.

a. The main critique to be checked: EI as white noise

According to its definition EI shows the amount of primary energy needed to generate one unit of GDP in a given country and year. The indicator is mostly used in time series to study the declining ratio of energy use per unit of GDP and the corresponding increase in energy efficiency. In fact, such a research can be carried out at different levels – at the national level or at the sector/industry level of a given country or panel (Sue Wing 2008). In the latter approach the sectoral EI makes it possible to focus on the energy-efficiency of technology deployed in particular sectors.

However, the use of EI indicator at the level of the whole economy is more problematic and it has been criticized by Giampietro et al. (2011) using the following claim: the ratio between "energy consumption per year" and "GDP per year" is "*a number without an external referent*". To support this point they illustrate the example of the value of EI of El Salvador, a developing country, which is exactly the same as that of Finland, a highly industrialized country. In their criticism they say that this is a systemic feature that can be easily explained when considering that the metabolic pace of energy per hour (the energy invested in producing and consuming goods and services) is reflected in the level of GDP per hour (reflecting the economic activity of producing and consuming goods and services). Both variables are indicators of the aggregate pace of production and consumption of goods and services in a given economy referring to different methods of quantification (energy flows versus monetary flows).

Assuming that GDP and energy consumption are correlated (Giampietro et al 2011, Ch. 3) translates into saying that an indicator such as EI - based on their ratio - should be considered a "white noise indicator" rather than a measure of economic efficiency. As previously mentioned, it is well known that a straight cross-country comparison shows that energy consumption and GDP are highly correlated. The long run correlation between GDP and energy in the US was highlighted by Cleveland et al. (1984), Hall et al. (1986), while Kaufmann (1992, p. 55) biophysical model for France, Germany, Japan and the United Kingdom, found that the "link between economic activity and energy use is stronger than believed", and "attempts to reduce the environmental impacts of energy production and consumption will be more expensive than is commonly assumed", pointing to the role played by energy quality for ensuring GDP growth[2].

But when carrying out a study over a large sample of countries (e.g. 133 countries of the world) and when considering a large time window (e.g. 1960-2010) can we generalize this conclusion? With this paper, I want to explore this idea and answer these questions.

2.3 Results of the empirical analysis

The EI indicator for 133 countries over the 1960-2010 time frame has been calculated using data on primary energy use from the International Energy Agency (2012) and real purchasing power parity international US$ GDP and population gathered by Gapminder (2011 a, b) from various sources (the GDP is from IMF). In this study I use two different approaches to check the validity of

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[2] Concerning the analysis of the role of energy quality for growth see also Stern and Kander (2010).

the results of the EI indicator to study changes in socio-economic characteristics of countries: (i) an analysis of the ability of detecting differences from countries at a given point in time (synchronic analysis, i.e. data describing the characteristics of a set of countries in a given year); (ii) an analysis to detect the differences of behavior of countries in time (diachronic analysis, i.e. time series used to describe the changes of a given set of countries). The two approaches are described in the following sub-sections.

2.3.1 The synchronic analysis of the sample of 133 countries in 2009

The resulting 2009 EI indicator, presented in *Table 3.1* is expressed in MJ per international 2005 real dollar (MJ/US$2005ppp)[3]. Very poor countries (GDP < 2000$) do have an important fraction of their economic activity outside market transaction (subsistence). Thus, the consumption of energy for producing and consuming goods and services does not translate into the generation of a relative amount of GDP – a large fraction of these goods and services are not market-traded. For this reason, the EI of some of these countries tend to be much higher than the rest[4].

While OECD countries have high values of both energy and income, many Asian, African and Latin American countries lay behind in the development stage. Countries having a high EI are mostly countries with low income suggesting that it is the denominator - i.e. GDP - making the difference in EI, because of the large fraction of economic activity associated with the production and consumption of goods and services taking place outside the market. Moreover, in developing economies a large fraction of the energy used is non-commercial energy, which is greatly underestimated in energy statistics, while, at the same time, the vast majority of activities which in developed countries would belong to the service sector is carried out outside the market. Finally, these countries do not express the same relation between energy consumption and GDP found in developed countries.

For all these reasons, if we want to focus on the possibility of studying the effect of technological development on the dematerialization of the economy (the decoupling of economic growth from consumption of energy and other resources) it is important to focus on a sample of countries expressing similar characteristics in their socio-economic structure.

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[3] For our purpose of (wide) comparison, we use 2009 as reference year, even though for some countries 2010 data are available.

[4] The 21 countries with GDP p.c. < 2000$ have an EI between 7.6 and 71.9 (with the exception of Bangladesh).

Table 2.1 Energy intensity of world countries

Energy Intensity in 2009 (MJ/$)					
Hong Kong, China	2.29	Croatia	5.85	Estonia	9.06
Peru	2.93	Yemen, Rep.	5.87	Canada	9.14
Albania	3.44	Senegal	5.98	Haiti	9.19
Panama	3.47	Latvia	6.00	Indonesia	9.33
Botswana	3.52	Azerbaijan	6.08	China	9.80
Singapore	3.59	Hungary	6.13	Belarus	10.05
Cyprus	3.75	Serbia	6.14	Jordan	10.13
Malta	3.78	El Salvador	6.14	Oman	10.20
Ireland	3.81	Romania	6.15	Myanmar	10.44
Congo. Rep.	3.88	Poland	6.25	Iran	10.52
Switzerland	3.90	Sweden	6.38	United Arab Emirates	10.66
Greece	3.94	Egypt	6.40	Syria	10.72
Gabon	4.00	Namibia	6.46	Eritrea	10.87
Colombia	4.12	Bolivia	6.66	Moldova	10.98
United Kingdom	4.30	Slovak Republic	6.69	Kuwait	11.25
Denmark	4.32	Macedonia, FYR	6.77	Libya	11.32
Spain	4.33	Belgium	6.97	Vietnam	11.52
Italy	4.37	New Zealand	7.02	Nepal	11.57
Sri Lanka	4.42	Lithuania	7.04	Benin	11.60
Austria	4.44	Turkey	7.08	Kyrgyzstan	11.66
Uruguay	4.45	Jamaica	7.11	Saudi Arabia	11.66
Costa Rica	4.68	Honduras	7.13	Ghana	11.74
Luxembourg	4.69	United States	7.13	Iraq	12.46
Ecuador	4.74	Australia	7.30	South Africa	13.26
Portugal	4.76	Georgia	7.32	Kenya	13.30
Morocco	4.80	Brunei	7.46	Nigeria	13.59
Israel	4.88	Cameroon	7.56	Russia	13.90
Tunisia	4.96	Czech Rep.	7.67	Bahrain	13.99
Norway	5.11	Algeria	7.67	Cote d'Ivoire	14.74
Lebanon	5.18	Paraguay	7.74	Tanzania	15.46
Germany	5.19	Armenia	7.80	Mongolia	15.60
Japan	5.26	Tajikistan	8.06	Kazakhstan	16.40
Angola	5.31	Pakistan	8.07	Zambia	17.93
Dominican Rep.	5.41	Malaysia	8.08	Ukraine	18.45
Chile	5.43	Korea, Rep.	8.38	Iceland	19.81
Brazil	5.44	Qatar	8.42	Mozambique	20.13
Netherlands	5.48	Cambodia	8.48	Korea. Dem. Rep.	20.36
Philippines	5.54	Finland	8.50	Ethiopia	20.75
Sudan	5.61	Thailand	8.54	Togo	20.98
Bangladesh	5.65	India	8.58	Turkmenistan	28.88
Guatemala	5.69	Nicaragua	8.73	Uzbekistan	29.12
Argentina	5.75	Venezuela	8.94	Trinidad and Tobago	35.60
France	5.77	Bulgaria	8.95	Congo, Dem. Rep.	41.66
Mexico	5.80	Bosnia & Herzegovina	9.01	Zimbabwe	71.96
Slovenia	5.82				

As soon as we enter in the group of country with a fair level of market transactions in the economy – e.g. when the GDP increases over the threshold of 5,000$ p.c. in 2009 (*Table 2.2* and *Figure 2.1* presents a cross-section comparison of the EI for the selected countries) - we find that the growing correlation between “energy” and “GDP” tends to unify the values of EI across countries, even if they are operating at very different levels of economic growth. Then, to work on a more robust sample: 1) I selected the 88 countries with a GDP > 5,000$p.c.; 2) I ranked the countries by their EI values; 3) I split the sample into 5 quintiles; 4) I took out the 1st and 5th percentile to remain with 52 countries expressing a quite similar value of EI divided into three groups: low, middle and high EI countries[5]. Therefore, the resulting three groups are defined as follows: Low EI country group including the countries of the second quintile, the Medium EI group including the countries of the third quintile, the High EI group including the countries of the fourth quintile. In this way, we can better focus on the differences or similarity of the set of countries belonging to the same cluster characterized by a very similar value of EI.

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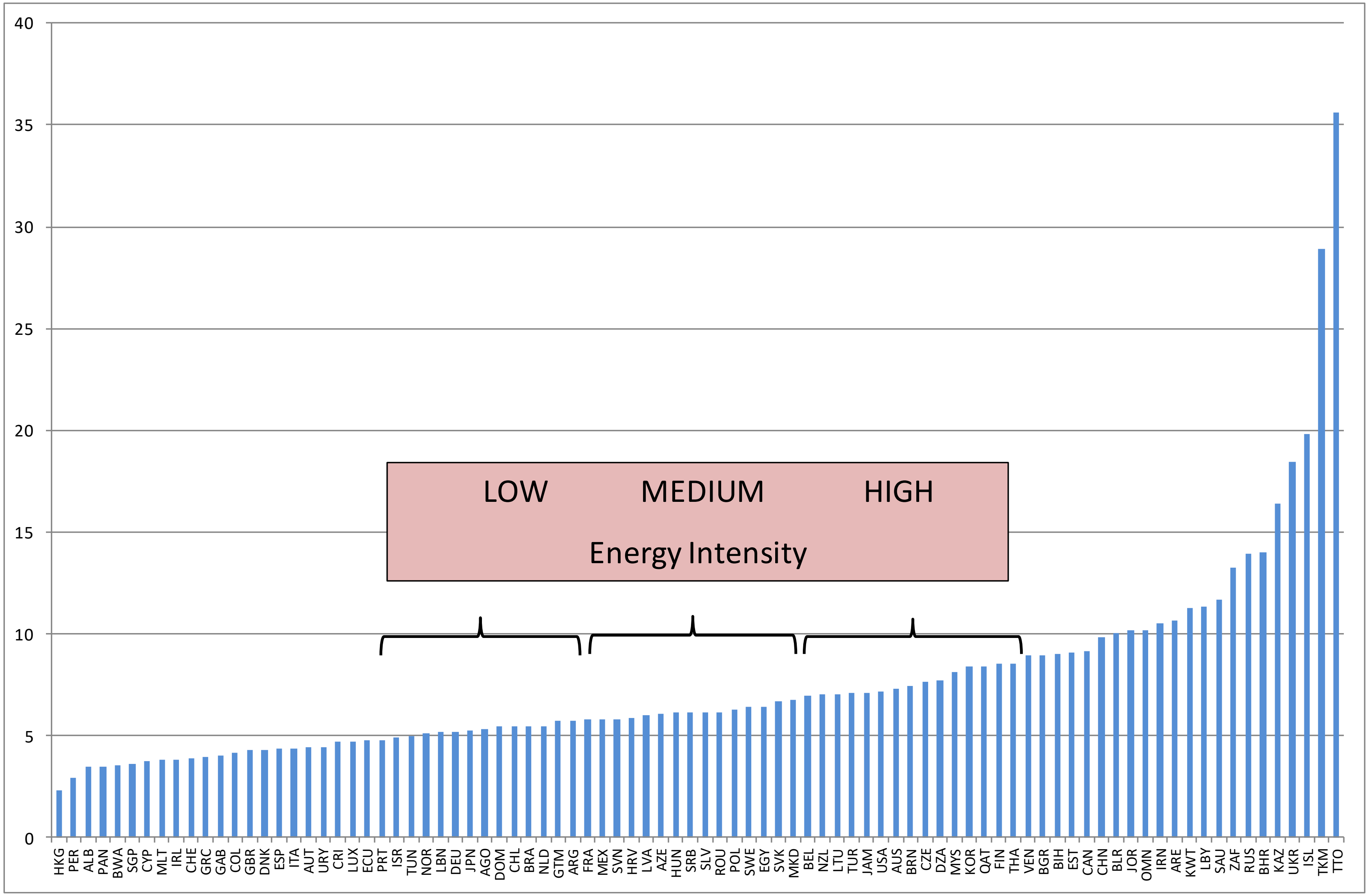
[5] To note, the 1st quintile included some of the main EU countries characterized by low-EI, e.g. Denmark, Greece, Ireland, Italy, Spain, Switzerland and United Kingdom. On the contrary, the 5th quintile included most energy-rich states, but also Belarus.

Table 2.2 Sample of countries with GDPp.c. > 5000$ in 2009, data and partition

Country	GDPp.c. (ppp$)	Energyp.c. (MJ/hab)	EI (MJ/$)	Population	GDP	correlation (70-09)	Quintile Group
Hong Kong, China	39.086	89.509	2.29	6.987.976	273.134.773.146	0.91	
Peru	7.859	23.043	2.93	28.765.162	226.064.632.832	0.34	
Albania	6.546	22.519	3.44	3.192.723	20.900.424.495	0.03	
Panama	10.797	37.495	3.47	3.461.901	37.377.036.739	0.01	
Botswana	12.282	43.281	3.52	1.981.576	24.338.279.319	0.87	
Singapore	43.526	156.419	3.59	4.945.645	215.264.354.968	0.77	
Cyprus	25.643	96.205	3.75	1.090.473	27.963.485.381	0.94	
Malta	21.328	80.630	3.78	415.220	8.855.748.852	0.89	
Ireland	35.693	136.076	3.81	4.412.181	157.483.749.035	0.94	
Switzerland	38.004	148.073	3.90	7.621.211	289.635.860.428	0.81	
Greece	27.626	108.824	3.94	11.326.596	312.909.780.516	0.94	
Gabon	12.705	50.838	4.00	1.477.514	18.771.806.485	0.52	
Colombia	7.091	29.193	4.12	45.654.044	323.718.753.767	0.43	
United Kingdom	31.042	133.628	4.30	61.652.315	1.913.840.163.232	-0.04	
Denmark	32.670	141.001	4.32	5.524.874	180.497.949.927	-0.16	
Spain	26.812	116.074	4.33	45.638.113	1.223.645.742.686	0.98	
Italy	26.161	114.410	4.37	60.248.654	1.576.140.199.050	0.98	
Austria	35.636	158.371	4.44	8.369.639	298.263.944.992	0.97	
Uruguay	11.461	51.047	4.45	3.357.391	38.479.175.297	0.57	Low
Costa Rica	9.552	44.677	4.68	4.590.790	43.849.218.541	0.86	
Luxembourg	70.857	332.297	4.69	497.637	35.261.291.697	-0.51	
Ecuador	7.035	33.327	4.74	14.261.566	100.336.576.779	0.51	
Portugal	19.898	94.668	4.76	10.657.175	212.061.054.485	0.99	
Israel	25.464	124.243	4.88	7.260.949	184.890.588.427	0.85	
Tunisia	7.500	37.164	4.96	10.365.089	77.734.093.014	0.94	
Norway	47.915	244.645	5.11	4.834.002	231.619.035.259	0.96	
Lebanon	12.766	66.168	5.18	4.196.990	53.579.662.514	0.63	
Germany	31.191	161.844	5.19	82.405.365	2.570.317.934.267	-0.18	
Japan	29.681	156.160	5.26	126.551.705	3.756.140.877.445	0.96	
Angola	5.056	26.843	5.31	18.555.115	93.806.982.082	0.03	
Dominican Rep.	6.388	34.588	5.41	9.796.852	62.577.908.954	0.76	
Chile	13.087	71.077	5.43	16.955.737	221.906.111.417	0.94	
Brazil	9.570	52.035	5.44	193.246.610	1.849.327.424.773	0.89	
Netherlands	36.075	197.665	5.48	16.559.268	597.367.848.217	0.63	
Guatemala	5.163	29.364	5.69	14.033.623	72.458.711.807	0.73	
Argentina	13.498	77.599	5.75	40.062.470	540.765.014.945	0.54	Medium
France	29.775	171.797	5.77	62.444.770	1.859.283.970.285	0.96	
Mexico	11.250	65.268	5.80	112.033.369	1.260.416.546.068	0.82	
Slovenia	24.778	144.159	5.82	2.024.040	50.152.089.606	0.56	
Croatia	14.110	82.608	5.85	4.410.864	62.239.339.515	-0.05	
Latvia	13.022	78.130	6.00	2.261.380	29.447.549.628	0.31	
Azerbaijan	9.088	55.269	6.08	9.066.604	82.401.080.092	0.65	
Hungary	16.983	104.062	6.13	10.002.247	169.866.114.524	0.49	
Serbia	10.005	61.413	6.14	9.851.440	98.565.806.217	-0.70	
El Salvador	5.647	34.677	6.14	6.160.423	34.786.997.278	0.75	
Romania	10.868	66.889	6.15	21.537.219	234.069.042.325	0.47	
Poland	16.466	102.884	6.25	38.249.228	629.804.297.025	-0.43	
Sweden	32.021	204.191	6.38	9.311.110	298.148.342.562	0.61	
Egypt	5.914	37.825	6.40	79.716.203	471.448.974.334	0.98	
Slovak Republic	19.186	128.426	6.69	5.451.968	104.601.539.498	0.05	
Macedonia. FYR	8.365	56.606	6.77	2.056.769	17.204.450.810	-0.10	
Belgium	32.257	224.722	6.97	10.660.938	343.886.046.655	0.88	
New Zealand	24.009	168.567	7.02	4.322.628	103.783.977.604	0.85	
Lithuania	14.929	105.112	7.04	3.341.097	49.878.508.105	0.88	High
Turkey	8.041	56.914	7.08	71.846.212	577.699.861.047	0.99	
Jamaica	7.024	49.937	7.11	2.730.774	19.180.243.315	0.46	
United States	41.256	294.329	7.13	307.686.729	12.693.949.488.187	0.01	
Australia	34.327	250.564	7.30	21.902.300	751.845.929.336	0.97	
Brunei	44.739	333.759	7.46	391.837	17.530.392.956	-0.19	
Czech Rep.	21.968	168.408	7.67	10.439.735	229.339.170.724	0.17	
Algeria	6.207	47.629	7.67	34.950.168	216.941.603.076	0,73	
Malaysia	12.388	100.110	8,08	27.949.395	346.227.995.242	0,99	
Korea, Rep.	23.875	200.060	8,38	47.963.923	1.145.153.877.709	0,99	
Qatar	74.138	624.330	8,42	1.597.765	118.455.553.692	-0,33	
Finland	30.603	260.004	8,50	5.341.546	163.465.896.678	0,94	
Thailand	7.376	62.961	8,54	68.706.122	506.788.148.186	0,98	
Venezuela	10.986	98.213	8,94	28.519.913	313.317.045.666	-0,09	
Bulgaria	10.840	97.034	8,95	7.542.674	81.764.551.501	0,27	
Bosnia and Herzegovina	7.342	66.150	9,01	3.767.683	27.662.255.885	0,61	
Estonia	16.349	148.189	9,06	1.341.629	21.934.473.121	0,85	
Canada	34.570	315.957	9,14	33.675.448	1.164.147.805.657	0,86	
China	7.226	70.795	9,80	1.334.908.820	9.646.147.265.852	0,96	
Belarus	11.574	116.278	10,05	9.636.016	111.531.401.236	0,88	
Jordan	5.109	51.773	10,13	6.025.592	30.787.126.678	0,87	
Oman	22.805	232.549	10,20	2.712.141	61.849.980.472	0,89	
Iran	11.742	123.571	10,52	73.137.148	858.744.087.041	0,48	
United Arab Emirates	33.735	359.578	10,66	6.938.815	234.080.532.150	-0,16	
Kuwait	42.444	477.404	11,25	2.646.286	112.317.723.145	-0,33	
Libya	12.052	136.421	11,32	6.262.667	75.475.304.545	-0,89	
Saudi Arabia	21.138	246.535	11,66	26.809.105	566.695.706.968	-0,54	
South Africa	9.141	121.223	13,26	49.751.503	454.791.777.184	0,20	
Russia	13.625	189.330	13,90	143.064.078	1.949.212.735.535	0,92	
Bahrain	24.227	338.990	13,99	1.169.578	28.334.794.322	0,46	
Kazakhstan	10.612	174.010	16,40	15.841.096	168.110.292.246	0,89	
Ukraine	5.731	105.760	18,45	45.715.010	261.986.545.899	0,90	
Iceland	34.990	693.299	19,81	315.543	11.040.763.031	0,95	
Turkmenistan	5.703	164.664	28,88	4.979.672	28.397.366.344	0,86	
Trinidad and Tobago	17.826	634.673	35,60	1.336.349	23.821.817.744	0,95	

Figure 2.1 Energy intensity of countries with GDPp.c. > 5000ppp$ in 2009



In order to visualize of the level of energy-GDP correlation within each cluster, I have represented the values of both "energy use per capita" and "GDP per capita" in a graph having these two variables on the two axes. The graphs characterizing the countries included in the three clusters are shown in *Figures 2.2*, *2.3* and *2.4*. The two variables determining the value of EI are shown using a two-variable (scatter) graph to highlight the diversity of the values of each one of these two variables: (i) energy (consumption per capita); and (ii) economic (real international GDP per capita). These figures clearly show the limits of the mono-dimensional perspective offered by the EI indicator. In fact, by doing this exercise one can finally discover that the countries included in the same cluster of EI values are basically lying on a straight regression line: the diagonal of the plane defined by the two variables "energy per capita" and "GDP per capita"[6]. The distance of the values of both "energy per capita" and "GDP per capita" found in each group clearly illustrates that the extreme heterogeneity of the economies considered in the analysis within each cluster. This heterogeneity is clearly visible when considering just a dimension at the time (how distant are the countries when considering either the value of GDP p.c. or when considering the value of energy consumption p.c.). However their position on the same regression line implies that they do express similar values of EI when considering the ratio of these two variables. Coming to the detailed analysis of these three groups:

i) the low-EI countries group is presented in *Figure 2.2*. It spans from Angola to Luxembourg, including Latin American and Caribbean countries, together with Germany, Japan and the Netherlands. All these countries are in the narrow range of EI = 4.45/5.69 MJ/$[7]. This range of EI values obviously hides the substantial differences between countries belonging to completely different typologies: agrarian, developed industrial and service economies.

ii) the middle-EI countries group is presented in *Figure 2.3*. It includes Egypt and El Salvador, Belgium and Sweden, together with some Eastern Europe countries, Mexico and Argentina. All these countries are within a range of EI between 6.14/6.97 MJ/$. Also in this case, we find extremely diverse typologies of economies sharing a similar value of EI.

iii) the high-EI countries group is presented in *Figure 2.4*. It includes higher income countries, like Finland, Australia and the USA together with Algeria, Bosnia and Bulgaria, Qatar and Brunei. All these countries are included in the narrow range of EI = 7.04/9.06MJ/$s. In this cluster, we must remark that the differences in both GDP p.c. and energy consumption per capita are very large: the GDP varies of a factor of almost 11 and the energy by a factor of 13.

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[6] The regression line R^2 is > 0.97 for the three groups.

[7] The size of the bubble in the Figures 1, 2 and 3 indicates real GDP in 2009.

Figure 2.2 Low EI countries group

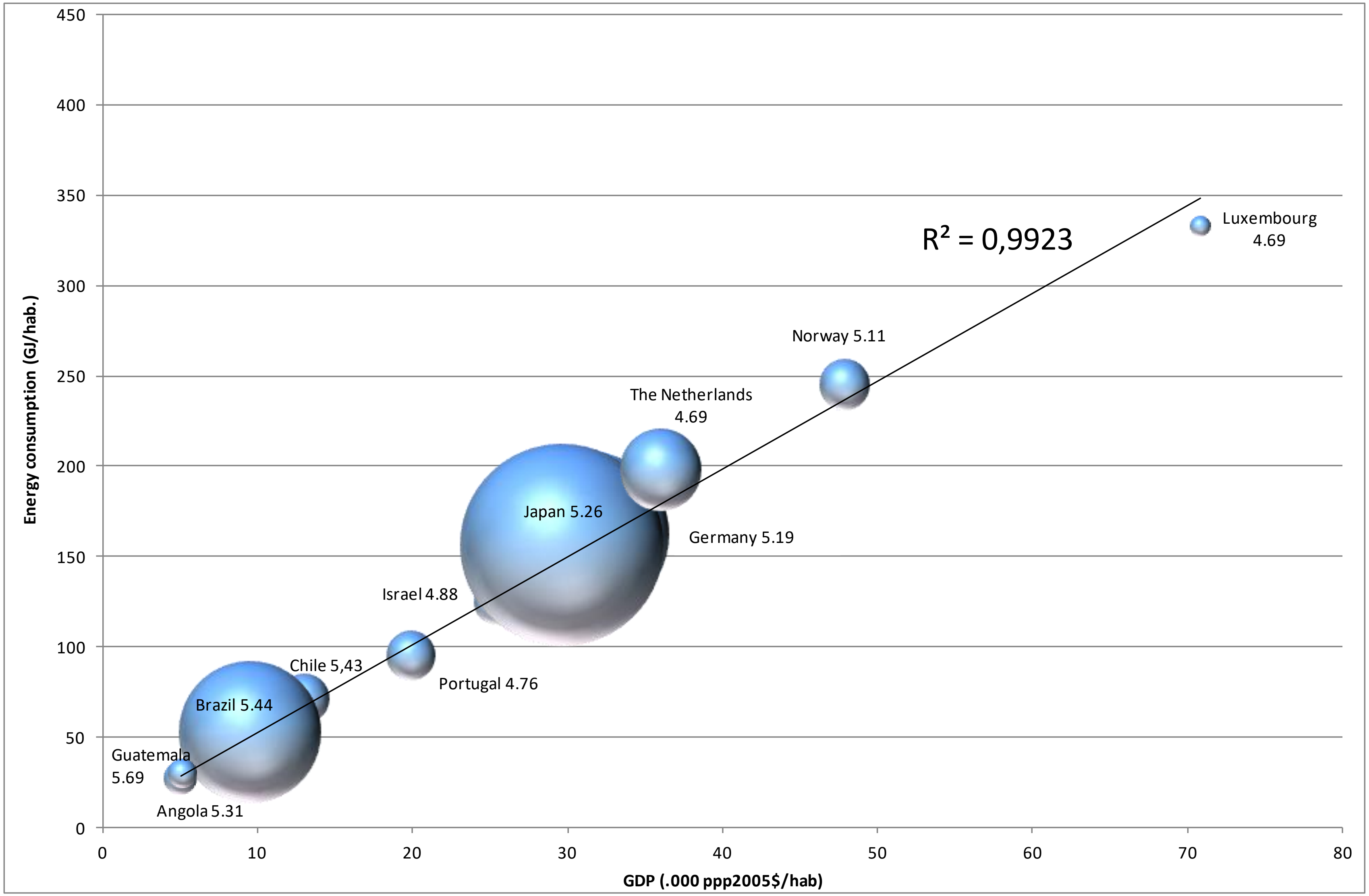


Figure 2.3 Middle EI countries group

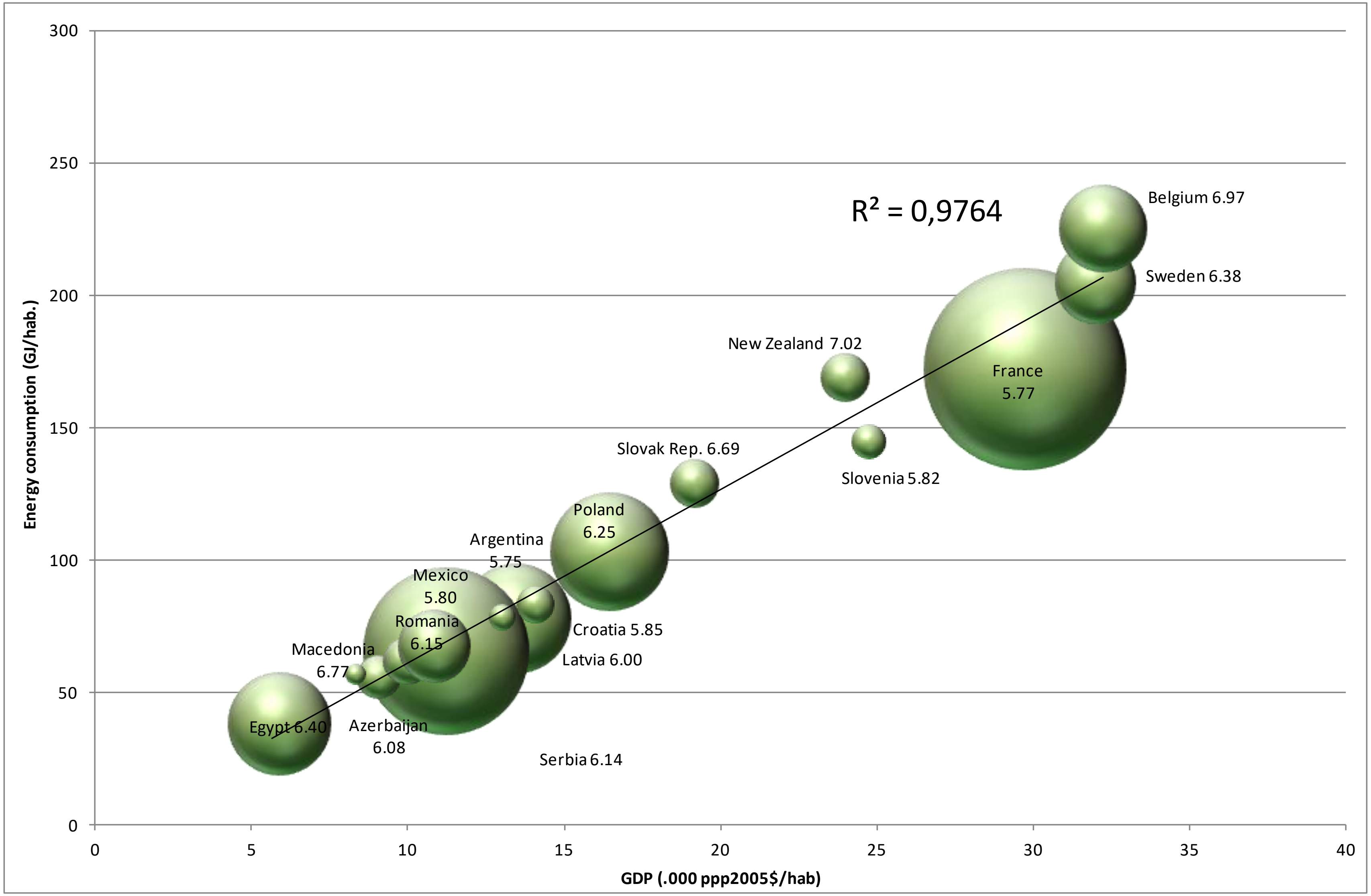
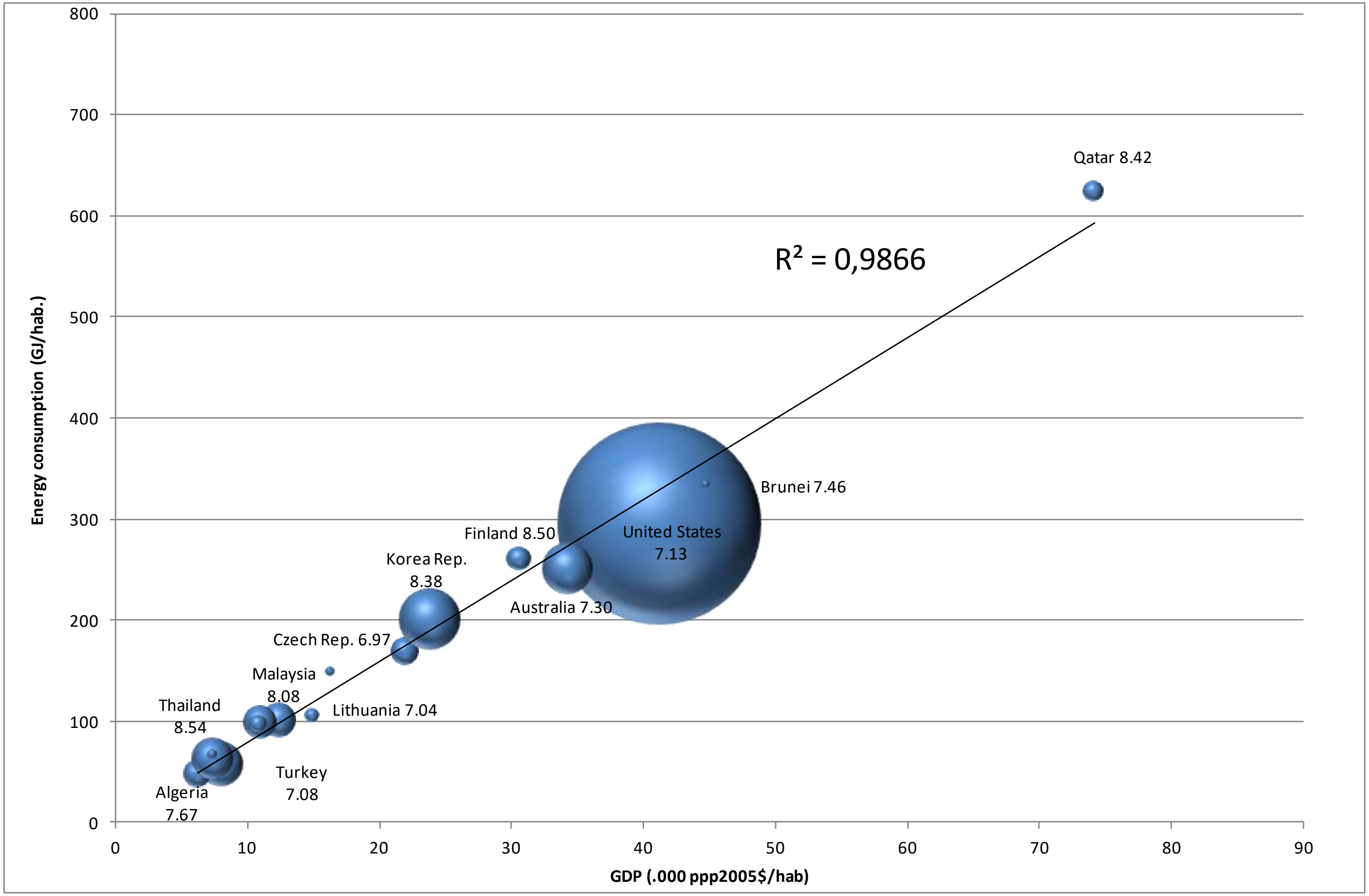


Figure 3.4 High EI countries group



2.3.2 The diachronic analysis of the sample of 133 countries between 1960- 2010

This unconventional analysis of the semantic validity of the information provided by the value of EI calculated at the level of whole countries can be extended to a diachronic analysis of the behavior of the sample of 133 over the period of time 1960-2010. Also in this case I use a representation based on a graph with the same two axes used in *Figure 2.2*, *2.3* and *2.4*, but this time a video is used to show the behavior of the sample of countries in time. The video can be seen at: http://tinyurl.com/b8l5ybq.

When looking at this video it is quite obvious that there is no common trend determined by technological progress in the trajectory describing the movements of the countries included in the sample. Starting approximately in year 2000, the video shows two phenomena: 1) major Asian countries (e.g. China and India), increase their energy use per capita (as well as EI), corresponding with export rise; 2) OECD countries reduce their energy use per capita (and EI), when starting to import energy intensive products from the former. For obvious reasons the most erratic countries are those of the Middle East, where little population benefits from giant fossil energy exports and where small changes in the ratio between export and internal use determine big “jumps” in the position over the graph.

Figure 2.5 Diachronic analysis (video screenshot)

2.4 Discussion

When considering the synchronic analysis of the 88 countries with GDPp.c. > 5000 US$/year, the characterization given by the EI indicator shows that the majority (58) of world's countries are included in a range between 4 and 9 MJ/US$, while western Europe countries EI lies between 4 and 6 MJ/US$, an exception is Belgium (7MJ/US$), while Iceland is a clear outlier (11MJ/US$) because of its extraordinary geothermal sources. However, if rather than adopting an indicator based on a single number, we try to characterize the economies using explicitly the two variables determining the EI indicator, providing two separate assessments based on energy use per capita *and* GDP per capita (e.g. on a plane), the resulting analysis becomes much more useful to characterize the biophysical performance of the economy.

In this richer analysis based on two variables, if we want to study the factors that generate the differences found over the two axes of both: (i) energy use p.c. (y-axis); and (ii) GDP p.c. (x-axis) the next "natural" analytical step is to open the black-box of the society and move to a sector-level description. By adopting a more complex analysis, it becomes possible to study how the EI of the economy can be explained by looking at: (i) the values of the "economic intensity" of the various economic sectors which is quite different for different sectors. In fact as shown by the analysis of Giampietro et al. (2011) Primary and Secondary sectors are much more energy intense than the Service and Government sector; and (ii) the relative size of these sectors determining their relative weight of sector-specific characteristics in the overall generation of GDP. In relation to this point we can flag to the reader that the MuSIASEM approach has been developed exactly to provide this type of insight about the different characteristics of structural and functional compartments of an economy determining the values of overall changes in the characteristics of the economy (Giampietro et al. 2009; 2011).

When considering the diachronic analysis of the 133 countries in the period 1960-2010 no generalized trend toward reduced values of EI can be detected. Commenting, one can say that beside the problem generated by neglecting the issue of scale (when assessing the characteristics of the economy at the level of the whole country there are too many factors affecting the EI) there are at least four reasons (the first has already been briefly described before) explaining why EI is not useful to carry out comparisons across countries at different level of economic development:

(1) both factors of the ratio making up EI have problems when used to characterize and compare typologies of very different economic systems. In relation to the assessment of the energy throughput p.c./year, the aggregation of different forms of energy can become

problematic when the quality of the various energy forms considered is quite different – e.g. electricity, coal, biomass (Giampietro et al. 2011; 2012). In relation to the assessment of GDP p.c./year, the assumptions about the (measurable) economic transactions forming GDP can imply: the missing of an important part of the economy both in very poor countries, where the majority of the population is engaged in activities taking place outside market transactions, and also in developed countries where GDP often does not reflect improvement in socio-economic performance, (van den Bergh, 2010);

(2) the EI ratio ignores differences in demographic characteristics (e.g. differences in dependency ratio) determining the requirement of activities in the service sector: ageing population requires more health services and longer studies implies delaying of work age and more educational services;

(3) the EI indicator "hides" the effects of externalization to other countries associated with the terms of trade, making possible the structural changes of the economy. In fact, the light-industry/service economy toward which post-industrial OECD countries converge is only possible because the activity of secondary (and a big part of primary) sector has been externalized to emerging economies – e.g. the BRICS. In this case, "there" (in the emerging economies) is the energy (and pollution) of the goods consumed "here" (in developed ones). As stated straightforwardly by Schaltegger and Csutora (2012, p. 2): "Much of the apparent reductions of carbon emissions [in the European Union] are due to the fact that they were 'exported' with major shifts of industrial production to Asia". The phenomenon of energy/pollution externalization can be seen clearly in the video showing the time series on two axes (described in Section 2.1);

(4) the increasing reliance of modern economies on credit leverage and debt muddles the possibility of detecting whether or not the goods and services consumed by developed countries (and not produced) have been paid by trading an equivalent value of goods and services produced in the importing countries or rather by making additional debt. So, from the national accounting information available, countries more effective in paying their import by making debt will be seen as more effective in "decoupling" their economies from energy use.

2.5 Conclusions

The answer to the title question is negative. As stated by Smil: "the EI ratio must be approached with great caution. If the measure is interpreted in a naive, ahistorical, and abstract fashion […] its use only reinforces some inaccurate notions, and it misleads more than it enlightens. Deconstruction of the measure offers a deeper understanding of underlying realities, uncovers a number of serious data limitations, leads to a careful interpretation of differences in levels and trends, and helps to avoid simplistic, and hence potentially counterproductive, conclusions." (Smil, 2003, pp. 70-71).

Since the energy throughput of an economy and GDP are highly correlated, their ratio cannot give useful information about the state of economic development in relation to the decoupling or dematerialization of modern economies. In this unconventional empirical analysis I decided to go for a semantic quality check, rather than for another "rigorous" formal test of this fact. Maybe using an approach based on simple common sense may result more effective in detecting systemic problems in the choice of indicators.

Probably, the success of the EI indicator may be explained by the fact that it can be used to support "rosy hypotheses" about the sustainability of modern economies – e.g. economic dematerialization of developed economies and Environmental Kuznets Curve (EKC) (Vehmas et al. 2007). Put it in another way, the EI indicator is used to provide empirical evidence of the decrease in the consumption of energy per unit of economic activity, which is explained by increases in efficiency – the effect of "the invisible hand" of the market and human ingenuity teaming together - ultimately resulting in better environmental performance: lower emissions per unit of GDP. However, a more detailed analysis of the same trends, carried out across multiple scales provides a different picture. The societal transition toward the service economy experienced by advanced economies, is determined by an externalization of energy and pollution to the countries producing the (now) imported goods (Giampietro et al. 2011) and, therefore, the approach of EI is far from satisfactory as an indicator of performance in relation to sustainability issues (Recalde and Ramos-Martin 2012).

To overcome the limits of the EI approach it is important to develop more complex descriptions of the functioning of modern economies avoiding the dangerous compression of non-equivalent information referring to different dimensions into aggregate indices referring to a single scale of analysis. An integrated assessment of sustainability requires the handling of different kind of information based on: 1) economic and biophysical dimensions; and 2) a multi-scale description capable to characterize in quantitative terms production and consumption across different compartments of the society.

3. Capital-energy substitution in manufacturing for seven OECD countries[8]

3.1 Introduction

From a resource economics perspective, when production is based on non-renewable resources - the case since the industrial revolution at the end on the 18th century - the ability to extend our current opportunities to future generations depends mainly on two factors: input substitution and technical change. In a simple but clear scheme, the output produced can be represented by a production function adopting a finite set of known inputs, like $y=f(K,L,E,M)$. While most functional specifications, like the Cobb-Douglas or the Constant Elasticity of Substitution feature input substitution by default, in many empirical studies the opposite is found. For example, energy is found to be a complement - or weak substitute - of capital. Other production functions, like the translog specification (Christensen, Jorgenson and Lau, 1973) are better at explaining why modern economies are heavily dependent on abundant, cheap fossil energy. In fact, many empirical findings indicate that reducing this dependence through more efficient technology using considerably less energy may hence be very difficult if not impossible.

The elasticity of substitution between inputs, a measure of production possibilities with different inputs shares, like energy and capital, or fossil and renewable energy, has been estimated for seven countries using a database with capital, energy, labour and raw materials as inputs. The article retraces how, from the classical Cobb-Douglas formulation with capital and labour inputs only, empirical production economics witnessed a turning point, coincident with the first energy crisis, when Berndt and Wood (1975) introduced energy and materials in their model of U.S. economy for the 1947-71 timeframe. They estimated a translog cost function (the dual of the production function), finding complementarity between capital and energy. Since then, in empirical research

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[8] This chapter was published as: Fiorito, G. and van den Bergh, J.C.J.M. (2016). Capital-energy substitution in manufacturing for seven OECD countries: learning about potential effects of climate policy and peak oil, *Energy Efficiency* 9(1), 49-65.

the two-inputs (capital and labour) formulation as well as Cobb-Douglas and Constant Elasticity of Substitution production functions lost appeal in favour of the translog KLEM specification.

Using the econometrics of a translog equation system, I model the output of the manufacturing sector of seven OECD countries[9] using capital, labour, energy and raw materials as input to estimate the elasticity of substitution between capital and energy between 1970 and 2005. The outcome includes a dataset and associated calculation procedure, estimates, inference and hypothesis testing. In parallel, I investigate both theory and various measures of the elasticity of substitution (which represent a conspicuous economics literature) and decided to employ the cross-price elasticity.

My study results confirm a general weak substitution between capital and energy over the period 1970-2005. Given that traditional economics evaluates the flexibility of an economy/sector to deal with varying inputs, if the future will be characterized by increasing energy scarcity, which is likely to result in high fossil prices, then capital/energy substitution is a synthetic indicator of system's robustness. Our results can be checked as the Stata procedures and database are available online for other years, sectors and countries to motivated researchers in the field.

3.2. The interrelated history of production functions and elasticity of substitution

Early production function formulations related total production to the amount of labour, capital and land employed in the economic process. Even though the merit of formulating this relation straightforwardly - production is a function of factors of production - is credited to Wicksteed (1894), the intuition of the mathematical relation might go back to Turgot's "partial derivatives of total product schedules", or to Malthus and Ricardo's "logarithmic and quadratic implicit functions" (Humphrey 1997). The Cobb-Douglas specification came into play when the economist Paul Douglas asked the mathematician Charles Cobb to develop an equation describing the time series of U.S. manufacturing output, labour and capital input he had assembled for the period 1889–1922. The result is the well-known expression: $P = bL^{k}C^{1-k}$, with P = production, L and C labour and capital respectively, b and k parameters; a function without land and raw material inputs, with constant RTS and fixed technology.

In the middle of the 20th century the search for flexible functional forms in the production specification was motivated by two conceptual needs. The first was to measure the 'ease' of substitution between production factors with no a priori restrictions (as imposed by the Cobb-Douglas). The second was the inclusion of other inputs, like different energy sources, the distinction

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[9] Namely, France, Germany, Italy, Japan, Spain, UK, USA.

skilled/unskilled labour force and raw materials. Thus, progress on production functions occurred because researchers looked for flexibility, i.e. realism, in input substitution.

One major step was the constant elasticity of substitution (CES) production function (Arrow et al. 1961), which encompasses the Leontief, linear and Cobb-Douglas production functions as special cases.[10] It writes: Q=F[aKr +(1-a)Lr]1/r, where, Q = output, F = factor productivity, a = share parameter, K, L = factor inputs and r = (s-1)/s, with s = 1/(1-r) the elasticity of substitution. Additionally, essential contributions of duality theory by Diewert (1974) and Fuss and McFadden (1978) led to modern input demand estimation practice via cost and, to a lesser extent, profit functions. The first study to use the dual cost function to derive input demand was Nerlove (1963). His models to estimate RTS and substitution between capital, labour, and fuels in the U.S. electric sector employed a cost function with non-constant RTS, rather than a production function. Nerlove, unsatisfied with the Cobb-Douglas specification, directed Daniel McFadden to work on both duality theory and flexible functional forms. While McFadden focused on duality theory, Diewert (a student of McFadden) devoted himself to the application of Shephard's theorem and the development of flexible functional forms with more than two inputs. In the early seventies, the flexible translog function was introduced by Christensen, Jorgenson and Lau (1971, 1973), although similar functional forms were produced a decade before.[11] The translog production function is written as:

$$\ln Q = \alpha_0 + \sum_{i=1}^{n} \alpha_i \ln x_i + \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \alpha_{ij} \ln x_i \ln x_j \tag{1}$$

where Q = output and x_i = input. Function (1) has the merit of relaxing both the Cobb-Douglas unitary elasticity of substitution and the CES constraints, where all production factors are substitutes by definition (Uzawa 1962).[12]

The history of the elasticity of substitution began with the first measures of factor substitution proposed by Hicks (1932) and Robinson (1933). Hicks introduced the elasticity of substitution to analyse the "ease of substitution" between capital and labour, while studying the effect of changes in income distribution in England. Robinson defined the elasticity of substitution more rigorously as the relative change in the demand for labour caused by a change in the relative price of factors. Shortly after, Hicks and Allen (1934) defined the elasticity of substitution as a measure of the responsiveness of relative inputs to relative input prices. Among the main challenges

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[10] When $s \to 1$ the function becomes the Cobb-Douglas, as $s \to \infty$ we get the linear (perfect substitutes) function; for s approaching 0, we get the Leontief (perfect complements) function.

[11] Heady and Dillon (1961) explicitly considered the second-degree polynomial expansion in logarithms (later called translog) and a square root transformation, which took on as a special case the generalized linear production function introduced by Diewert in 1971.

[12] An additional drawback of the CES is that the elasticity of substitution is the same for all inputs, which is quite unrealistic.

related to the elasticity of substitution are: inputs measurability in monetary and physical units; input separability (Frondel and Schmidt 2004) and the choice of substitution measure among a multitude of elasticity formulas.[13]

The academic research on capital-energy (*K-E*) substitution reached a milestone with the econometric work of Berndt and Wood (1975): they used the translog production function to derive the dual cost function and the input shares from Shephard's lemma and they estimated *K-E* elasticities employing an original database of capital (*K*), labour (*L*), energy (*E*) and materials (*M*) for the manufacturing sector in the United States.[14] Their results indicated a clear complementarity between *K* and *E* with an estimated Allen elasticity of substitution between energy and capital of *-3.53* in 1971, corresponding to a cross-price elasticity (CPE_{ke}) of *-0.16*.

After this study, a vivid debate on *K-E* substitutability emerged as further research provided different estimates of substitution elasticities at national, industrial and inter-country levels, even for the same country and sector. Several explanations for the variety of findings have been offered: first of all time-series capture short-term (low) substitution, resulting in a bias towards *K-E* complementarity, while cross-section data represent long-term input equilibria, showing substitutability between the factors (Apostolakis 1990) [15]; then the inclusion of material inputs in the specification increases *K-E* complementarity (Frondel 2001, p.49). Finally, separating between physical and working capital results in an increased complementarity between physical capital and energy (Field and Grebenstein 1980). Solow (1987) raised doubts about possible aggregation bias in substitution estimates at the aggregate manufacturing level as, in a strict sense, *K-E* substitution is a microeconomic phenomenon determined by engineering and organizational constraints.

In a sharp critique, Miller (1986) pointed at the role and bias induced by the different output composition between countries and sectors. In any case, it became increasingly clear that what mostly affects the results is the definition of capital input. In fact, the capital input is calculated from national accounting data as the residual value added, after subtracting labour payments and the energy bill from national income.[16] A narrower approach to measure capital, denoted *capital services*, develops a physical index of capital, using the perpetual inventory method (PIM) where, starting with an estimated initial capital stock, yearly investment flows are added and a depreciation

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[13] For more details, the interested reader might check the extensive surveys by Frondel (2001), Koetse et al. (2008), Sorrell (2008) and Stern (2007).

[14] Since Berndt and Wood's contribution, the *K-L* formulation, the Cobb-Douglas and the Constant Elasticity of Substitution production functions lost research appeal in favour of the 4-inputs translog cost specification.

[15] For a given capital equipment, the energy input per unit of time is rather constant (*K-E* complementary) in the short run, thus an increase in energy prices is likely to lead to an increase in labour input (*L-E* and *L-K* substitutes) instead of capital, while, in the long run, energy-saving capital can be added, so *K* and *E* might turn into substitutes (as well as *E* and *L*).

[16] The value added includes the contribution to production of a heterogeneous set of capital inputs, like residential buildings and financial products; these are joined into reproducible capital inputs (instead of being attributed to rent). For a review of studies estimating capital services see Baldwin and Gu (2007).

rate is subtracted. One shortcoming of the PIM approach is the constant capital depreciation rate and variations determined by investment flows. In fact, investment flows are a function of business cycles and are inversely correlated with energy prices. So, in times of cheap energy, machines scrapping is likely to accelerate (high investment cycle) and this is not accounted for (constant depreciation), leading to capital overestimation.

Historically, cheap energy and large investments characterized the U.S economy in the post-WW2 – pre-1973 timeframe, when capital-energy complementarity was assessed by Bernd and Wood (1975). Thus, in the cost function formulation, the evidence for *K-E* complementarity is limited to acknowledging that “investment lowers when energy prices grow or vice versa” (Miller 1986, p.755). Finally, as the PIM is a rent-weighted measure of capital services, if investments to an industry slowdown (or stop) then the capital input does not just stop growing but actually declines.

A literature review (Broadstock et al. 2007) of empirical *K-E* substitution studies covering more than 100 scientific papers found that 40% of the estimates assess complementarity between *E* and *K*, and within the remaining 60%, around two thirds are less than unity; hence, 75% of the estimates suggest that *E* and *K* are either complements or weak substitutes. Concerning the inclusion of material inputs in the specification, the review finds that half of the studies use three-input (*KLE*) and the other half a four-input (*K, L, E, M*, or similar) specification, with a clear distinct effect on the results: the average *K-E* elasticity of substitution in KLE specifications is between *0.4* and *0.5* (suggesting *K-E* substitution), while KLEM specifications result in an average estimated *K-E* elasticity of substitution of *-0.5* and median *-0.1*, indicating complementarity.

The level of aggregation is also an important cause of variability, since at the higher level a sector may still exhibit factor substitution due to changes in product mix, even if the mix of factors required at a lower level is relatively fixed. Koetse et al.’s (2008) meta-analysis of the literature finds a CPE_{ke} for North America and Europe of around *0.38* and *0.34* respectively, which can be interpreted as weak substitution characterizing the relation between energy and capital in the aggregate manufacturing sector. In general, estimates of cross-price elasticities are not significantly different from zero which means that the production structure is quite rigid and inputs cannot be easily substituted for one another. These results suggest that investment in production capital (including innovation) is probably not an effective way to reduce energy use, contrasting the decoupling hypothesis.

Other reasons for variation in the *K-E* elasticity are the assumptions made about the technology (homothetic or not), the inclusion of RTS parameters and the specification (or lack thereof) of TC. Here we employ the cross-price elasticity to assess substitution, which measures the variation in quantity of input *i* (e.g. capital) used in the manufacturing sector following a 1% variation on the price of input *j* (e.g. energy).

3.3. Data, models and measures

The EU-KLEMS database offers an opportunity to analyse the production structure at the sector level for different countries. It provides volumes and prices of capital, labour, energy and intermediate materials, from 1970 onwards.[17] It is the main outcome of a research project financed by the European Commission to analyse productivity at the industrial level, "embedded in a clear analytical framework, rooted in production functions and the theory of economic growth" (Timmer et al. 2007, p. 5). The 2008 EU-KLEMS release stops in 2005, while the coverage begins in 1970 for Italy, UK and USA, in 1973 for Japan, in 1978 for Germany, in 1980 for Spain and in 1981 for France. To our knowledge, this database has not been used to estimate translog cost functions or to derive measures of input substitution between energy and capital for the manufacturing sector.

The EU-KLEMS aggregation, over products or industries, uses the Tornqvist quantity index, a discrete time approximation to a Divisia index; labour compensation (LAB), is derived by applying the ratio of total hours worked by total persons engaged to hours worked by employees to compensation; capital compensation (CAP) is derived as value added minus LAB; finally, energy (E), materials (M) and services (S) inputs are calculated by applying the shares of E, M and S from the Use-tables to total intermediate inputs from the national account series.[18]

The KLEM input shares for the manufacturing sector in the countries analysed in year 2000 are presented in *Figure 3.1*. The USA have the highest capital share (16%, followed by France at 10%); the share of labour is the highest in UK and the lowest in France and Spain, while the energy shares lie in the 4-5% range except for Spain and Japan; materials share is 40% in the UK and above 50% in France, Italy and Spain.

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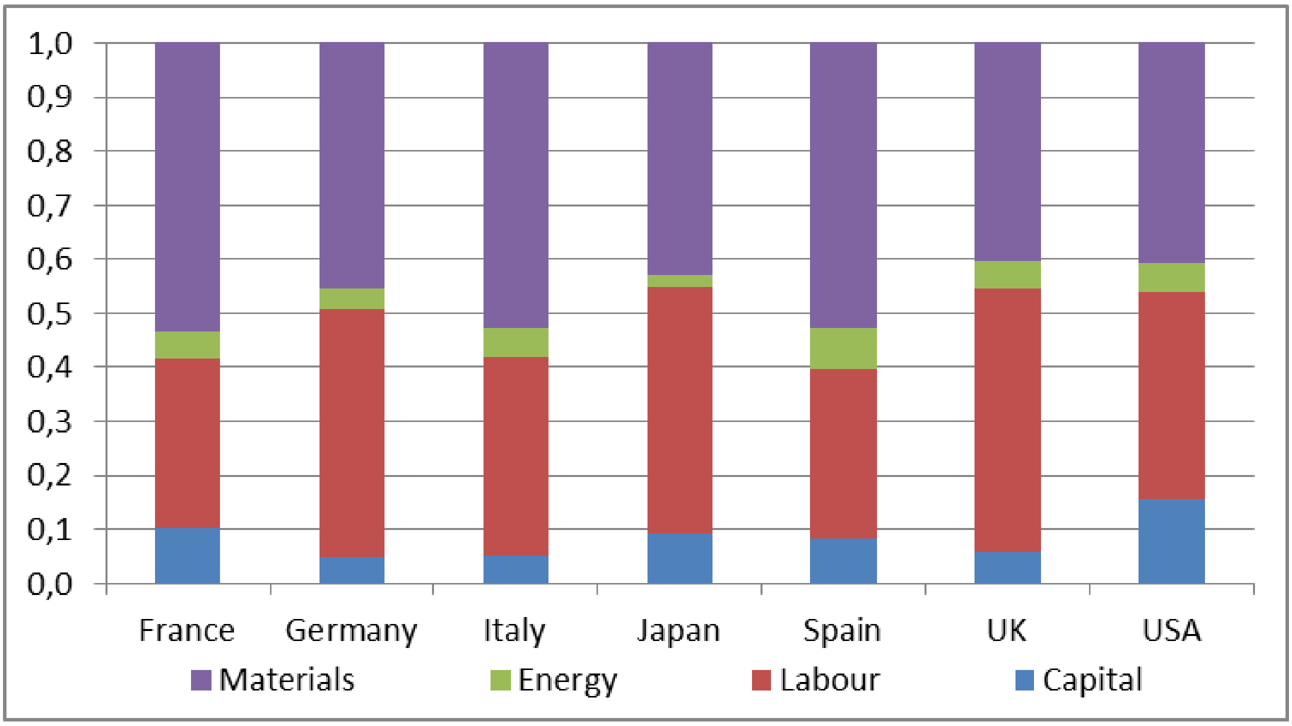
[17] We use the 2008 EU-KLEMS release, as the 2009 update does not include energy and materials and we opted for employing all available information since this meant that for most countries periods with important changes in energy prices could be included.

[18] While for many countries nominal Supply-Use Tables (SUTs) are available since 1995, few countries have SUTs going back to 1980 or earlier. Here Input-Output tables have been used to derive measures of E, M and S. Energy input is defined as all energy mining products (10-12), oil refining products (23) and electricity and gas products (40). All products from industries 50-99 are included as services; the remaining products are classified as materials.

Figure 3.1 Manufacturing sector input shares in year 2000



Source: author's calculation

The countries studied are comparable in terms of both wealth and degree of industrialization. We estimated translog cost specification (2), where C_t is total cost at time t; p_{it} is the i-th input price, y_t output, and t_t a time trend to quantify TC; RTS are captured by gross output y_t; and input-specific RTS and TC parameters are included via composite variables. The main reason to use a cost function (2) instead of a production function (1) is to circumvent the general problem that input quantities are not likely to be exogenous at the aggregate level, violating the necessary conditions for unbiased parameters (Binswanger 1973). The use of prices in the estimation solves the endogeneity problem, since they are more likely to be exogenous than the quantities (Diewert, 1974).

$$\begin{aligned}\ln C_t &= \beta_0 + \beta_y \ln y_t + \frac{1}{2}\beta_{yy} \ln y_t^2 + \beta_t t_t + \frac{1}{2}\beta_{tt} t_t^2 + \sum_{i=1}^{m} \beta_i \ln p_{it} \\ &+ \frac{1}{2}\sum_{i=1}^{m}\sum_{j=1}^{m} \beta_{ij} \ln p_{it} \ln p_{jt} + \sum_{i=1}^{m} \beta_{iy} \ln p_{it} \ln y_t + \sum_{i=1}^{m} \beta_{it} \ln p_{it} t_t + \varepsilon_t\end{aligned} \qquad (2)$$

The i-th input share (3) is obtained by deriving (2) with respect to p_i and applying Shephard's lemma.

$$S_{it} = \beta_i + \beta_{iy} \ln y_t + \sum_{j=1}^{m} \beta_{ij} \ln p_{jt} + \beta_{it} t_t \qquad (3)$$

The usual linear homogeneity in prices and symmetry constraints are assumed for the empirical implementation:

$$\beta_{ij} = \beta_{ji}, \sum_i \beta_i = 1, \sum_i \beta_{ij} = \sum_j \beta_{ij} = \sum_i \beta_{iy} = \sum_i \beta_{it} = 0 \tag{4}$$

In addition to (4), the regularity condition of cost minimization requires monotonicity of the cost function (to be non negative) and concavity in factor prices (the Hessian of second derivatives to be negative semi-definite). Finally, own and cross-price elasticities are derived from the estimated parameters as shown in *Table 3.1*.

Table 3.1 Elasticities and their variances

Elasticity	**Variance**
$\eta_{ij} = s_j + \frac{\beta_{ij}}{s_i}$	$\operatorname{var}(\eta_{ij}) = \frac{\operatorname{var}(\hat{\beta}_{ij})}{\hat{s}_i^2}$
$\eta_{ii} = \frac{\beta_{ii} + s_i^2 - s_i}{s_i}$	$\operatorname{var}(\eta_i) = \frac{\operatorname{var}(\hat{\beta}_{ii})}{\hat{s}_i^2}$

Note: s_i denotes the i-th input cost share $(p_i x_i / \sum p_i x_i)$

We jointly estimated cost function (2) and *K*, *L*, *E* cost shares by iterated three stage least squares, using Stata$^{(R)}$. The results are discussed in the next section.

3.4. Results

To assess model adequacy in describing the manufacturing sector technology, we tested four restricted versions of specification (2), resulting in various null hypotheses (H_0). The first states that all RTS and TC parameters are 0, the second that only the TC parameters are 0, the third that only the RTS parameters are 0, and a final one that input specific, crossed and non-linear TC and RTS parameters are 0. The χ^2 statistics results (*Table 3.2*) lead to retain the broad model (2).

Table 3.2 - χ^2 tests results

	Model 1		Model 2		Model 3		Model 4	
Constraint	$\beta_y=\beta_{yy}=\beta_t=\beta_{tt}=\beta_{ky}=\beta_{ly}$ $=\beta_{ey}=\beta_{kt}=\beta_{lt}=\beta_{et}=0$		$\beta_t = \beta_{tt} = \beta_{kt} = \beta_{lt}$ $= \beta_{et} = 0$		$\beta_y = \beta_{yy} = \beta_{ky} = \beta_{ly} =$ $\beta_{ey} = 0$		$\beta_{tt} = \beta_{yy} = \beta_{ky} = \beta_{ly} = \beta_{ey}$ $= \beta_{kt} = \beta_{lt} = \beta_{et} = 0$	
France	χ2 (13)	354.20	χ2 (7)	46.92	χ2 (6)	247.73	χ2 (11)	341.60
	Prob > χ2	0.0000		0.0000		0.0000		0.0000
Germany	χ2 (13)	384.85	χ2 (7)	86.18	χ2 (6)	187.18	χ2 (11)	327.74
	Prob > χ2	0.0000		0.0000		0.0000		0.0000
Italy	χ2 (14)	382.68	χ2 (7)	39.06	χ2 (7)	287.91	χ2 (12)	373.86
	Prob > χ2	0.0000		0.0000		0.0000		0.0000
Japan	chi2 (13)	420.23	χ2 (7)	122.89	χ2 (6)	321.46	χ2 (11)	406.60
	Prob> χ 2	0.0000		0.0000		0.0000		0.0000
Spain	χ2 (13)	303.36	χ2 (6)	41.84	χ2 (6)	189.08	χ2 (11)	284.15
	Prob > χ2	0.0000		0.0000		0.0000		0.0000
UK	χ2 (14)	409.60	χ2 (7)	75.52	χ2 (7)	217.41	χ2 (12)	399.40
	Prob > χ2	0.0000		0.0000		0.0000		0.0000
USA	χ2 (14)	502.51	χ2 (7)	139.10	χ2 (7)	268.57	χ2 (12)	433.65
	Prob > χ2	0.0000		0.0000		0.0000		0.0000

All null hypotheses were rejected at a high level of significance, so we retained the unconstrained specification (2). The next step was to analyse concavity of second partial derivative (verifying cost-minimizing behaviour). Thus, we employed a procedure to assess *KLE* eigenvalues at every sample point (Baum and Linz 2009). The results are in *Table 3.3*, and show that the number of positive eigenvalues is only zero for the USA and positive for the other countries. From these results we can infer that the regularity condition holds in all years for the US, in most years for Italy, Japan and the UK, while it does not hold for France, Germany and Spain. We conclude that the theoretical model does not fit the aggregate data for Spain as the positive eigenvalue is significantly high in all years; for France and Germany it is close to 0, which may reflect uncertainty about the true sign. Recall that the theoretical model only really makes sense anyway for an individual firm. Some assumptions are needed for it to fit aggregate data and so these results are not totally unexpected. A possible explanation for non-negative eigenvalues is the lack of variation in both capital and energy prices in these countries since their data series do not include the energy price shocks of 1973 and 1979. For completeness of information and because we verified that the fitted KLE cost shares were positive over all the sample period, in *Tables 3.4* and *3.5* the substitution results and the estimated parameters are reported for all countries.

Table 3.3 Information about Hessian eigenvalues

Country	Positive Eigenvalues	Sample	Positive Eigenvalues (%)
France	24	75	32%
Germany	28	84	33%
Italy	24	108	22%
Japan	10	99	10%
Spain	26	78	33%
UK	12	108	11%
USA	0	108	0%

Estimates for France produce slightly negative and highly significant cross-price elasticities, and a high labour price elasticity. Input-specific parameters are statistically significant, in particular neutral RTS. To compare, Griffin and Gregory (1976) obtain $\eta_{ke} = 0.11$ (but not significant) and $\eta_{ek} = 0.27$ (significant) with panel data for 1965; the η_{ke} estimates by Hesse and Tarkka (1986) for 1977, which is related to fossil fuels and electricity inputs, are not statistically significant.

Cross-price elasticities are negative and significant in Germany, with the exception of positive η_{kl}, indicating substitution between capital and labour; the neutral RTS parameter is highly significant. Previous German estimates by Welsch and Ochsen (2005) are $\eta_{ke} = -0.13$ and $\eta_{ek} = -0.32$; the only other significant estimates for Germany are by Falck and Koebel (1999), who obtain $\eta_{ke} = 0.01$ and $\eta_{ek} = 0.03$.

Cross-price elasticities for Italy are not significantly different from zero; all elasticities are below zero (-1.2 for labour) characterized by high t-values; RTS and TC parameters are generally not significant, with the exception of *K*-using TC. These results can be compared with Pindyck (1979) *KLE* model with panel data for 1965-1973 ($\eta_{ke} = -0.05$ and $\eta_{ek} = -0.28$), and Apostolakis (1990) who obtained *0.58* and *0.3*, respectively for 1984 (but no standard error was provided). Medina and Vega-Cervera (2001) estimate $\eta_{ke} = -0.02$ in 1988 (low significance), while Hesse and Tarkka (1986) obtain a just significant $\eta_{ke} = 0.027$ between capital and fossil fuels for 1977.

For Japan we obtain $\eta_{ke} = 0.01$ and $\eta_{ek} = 0.06$, which indicate weak substitution between *E* and *K*; own capital and energy price elasticity are *-0.6* and *-0.4*, respectively. Norsworthy and Malmquist (1983) estimate for Japan η_{ke} as *-0.37* for 1977 (but do not provide a standard error) in a model with constant RTS and biased TC; estimates by Pindyck (1979) show complementarity between energy and capital in the Japanese manufacturing sector.

The positive energy price elasticity for Spain is probably due to the lack of variation in Spanish energy prices, making it difficult for the model to capture the mechanism of price reaction. This is confirmed by a lack of significance of the β_k parameter. Nevertheless, significant and negative cross-price elasticities are reported ($\eta_{ke} = -0.84$ and $\eta_{ek} = -1.2$) supporting the hypothesis of complementarity, even though we consider Spanish elasticities to have a low reliability. The results can only be compared with Apostolakis (1987), who finds $\eta_{ke} = 0.49$ for 1984, and Medina and Vega-Cervera (2001), who estimate $\eta_{ke} = -0.0023$ for 1988 (not significant). Estimation results for the UK are unsatisfactory (*pseudo*-$R^2 = 0.15$ and *D-W = 0.26, i.e.* positive autocorrelation); the UK negative *K-E* elasticities can be compared with Hunt's (1986) estimates ($\eta_{ke} = 0.17$ in 1980) in a model with input-specific technical change. For the USA we obtain negative and significant capital and labour own-price elasticity, but non-significant β_e; cross-price elasticities are significant ($\eta_{ke} = -0.08$ and $\eta_{ek} = -0.10$), as are neutral RTS parameters. In the past, USA input substitution has been assessed by many studies at the subsector (2 digit) level, with only few studies treating the aggregate manufacturing sector; among them are Garofalo and Malotra (1984) and Moghimzadeh and Kymn (1986), who distinguish between electric and non-electric energy. The results of both refer to the 1970's and find weak substitution or complementarity in all cases.

Table 3.4 Estimated elasticities

	η_{ke}	η_{ek}	η_{kl}	η_{lk}	η_{le}	η_{el}	η_k	η_l	η_e
France	-0.0431	-0.0604	-0.2912	-0.0737	-0.0588	-0.3347	-0.3343	-1.0786	-0.2274
t-value	-16.97	-12.11	-312.31	-1328.88	-693.61	-119.50	-121.83	-16065.09	-26.59
Germany	-0.3659	-0.3476	0.1707	0.0198	-0.1471	-1.1080	-0.3207	-1.2399	0.9253
t-value	-24.83	-26.13	20.04	156.53	-42.11	-5.23	-283.60	-481.03	30.05
z\Italy	-0.0150	-0.007	-0.0642	-0.0104	-0.0286	-0.1114	-0.4087	-1.2827	-0.4961
t-value	-8.33	-17.01	-35.49	-494.10	-96.97	-18.28	-497.31	-4279.59	-72.96
Japan	0.0167	0.0625	-0.1185	-0.0366	-0.0156	-0.2193	-0.6005	-1.1912	-0.3996
t-value	13.57	3.64	-30.61	-118.28	-129.40	-10.43	-168.71	-2262.86	-19.30
Spain	-0.8406	-1.2058	0.3716	0.1311	-0.6627	-2.7271	-0.2760	-0.5689	3.2554
t-value	-125.55	-87.53	138.23	386.88	-168.15	-42.40	-187.52	-214.63	28.45
UK	-0.1688	-0.1450	-0.0911	-0.0097	0.1271	1.1125	-0.2581	-1.4933	-1.4895
t-value	-6.10	-7.10	-4.80	-29.37	16.16	3.36	-137.18	-243.29	-3.22
USA	-0.0769	-0.1038	-0.0101	-0.0063	0.0946	0.4973	-0.5442	-1.3060	-0.9626
t-value	-20.40	-15.12	-1.37	-12.11	49.39	10.15	-195.55	-423.07	-22.82

Significant capital-using TC is found except for Germany and Spain; energy-saving TC for France and Japan. Furthermore, significant energy-using RTS was found for France, Germany and Japan, and significant labour-saving RTS for France, Germany and Spain. In general, our estimations show that energy and capital are not substitutes as $\eta_{ek} < 1$. Overall, these results need to be carefully interpreted, since the hessian is not negative definite for all countries.

Table 3.5 Cost function parameters

	France		Germany		Italy		Japan		Spain		UK		USA	
Variable	Coef.	t-val.	Coef.	t-val.	Coef.	t-val.	Coef.	t-val.	Coef.	t-val.	Coef.	t-val.	Coef.	t-val.
β_k	-0.2489	-2.48	0.2519	4.96	-0.0773	-10.25	0.5696	8.19	0.0458	0.57	0.0003	0.01	0.3421	5.28
β_l	1.0720	14.45	1.1040	3.67	0.6917	26.32	0.3433	4.08	1.4230	7.76	1.1883	6.83	0.7181	5.41
β_e	0.1768	1.49	-0.2927	-0.94	0.3855	14.11	0.0870	1.66	-0.4688	-2.05	-0.1880	-0.88	-0.0603	-0.52
β_{kk}	0.0653	14.36	0.0433	21.94	0.0318	22.35	0.0536	8.47	0.0837	21.51	0.0502	18.54	0.0593	10.64
β_{ll}	0.0988	33.86	0.1158	4.75	0.0816	10.25	0.0690	8.02	0.2047	13.92	-0.0102	-0.28	0.0355	1.62
β_{ee}	0.0517	9.02	0.1227	3.61	0.0613	7.34	0.0178	4.37	0.3059	12.79	-0.0303	-0.61	0.0090	0.56
β_{kl}	-0.0562	-21.20	-0.0182	-3.36	-0.0260	-12.33	-0.0524	-7.93	0.0087	1.66	-0.0351	-4.09	-0.0429	-4.72
β_{ke}	-0.0091	-2.09	-0.0251	-3.52	-0.0057	-2.74	-0.0012	-0.33	-0.0924	-11.14	-0.0151	-1.45	-0.0164	-2.53
β_{le}	-0.0425	-12.98	-0.0976	-3.44	-0.0555	-7.02	-0.0166	-4.04	-0.2134	-11.90	0.0454	1.09	0.0073	0.42
β_y	1.5299	32.10	1.1776	20.89	1.6305	3.78	1.3869	76.69	1.4016	6.98	-2.8763	-4.52	-3.5598	-4.32
β_t	0.0170	3.74	-0.0299	-8.10	0.0130	-0.41	-0.0356	-13.52	-0.0774	-3.11	0.0076	0.51	0.0054	0.61
β_{yy}	-0.0814	-11.07	-0.0258	-3.12	-0.1178	-4.54	-0.0401	-20.95	-0.0655	-1.99	0.1935	3.97	0.2503	4.63
β_{tt}	0.0000	0.26	0.0002	0.87	0.0008	0.82	0.0014	12.67	0.0027	3.24	0.0001	-0.33	0.0013	-3.06
β_{ky}	0.0243	2.99	-0.0120	-2.70	0.0095	1.89	-0.0311	-8.16	0.0403	2.43	-0.0149	-2.71	-0.0231	-2.65
β_{ly}	-0.0559	-7.78	-0.0627	-2.76	0.0053	0.35	0.0084	1.86	-0.0692	-2.78	-0.0314	-1.45	0.0143	0.92
β_{ey}	0.0316	3.39	0.0748	2.99	-0.0149	-1.18	0.0226	7.48	0.0288	0.92	0.0464	1.94	0.0087	0.69
β_{kt}	0.0888	2.17	0.0000	0.02	0.0110	2.99	0.0110	8.54	-0.0157	-1.06	0.0163	6.45	0.0269	3.42
β_{lt}	0.0140	3.10	0.0119	1.66	-0.0082	-1.21	0.0006	0.35	0.0437	1.64	-0.0127	-1.18	-0.0004	-0.06
β_{et}	-0.0229	-4.36	-0.0198	-1.40	-0.0027	-0.41	-0.0116	-6.59	-0.0280	-1.05	-0.0035	-0.29	-0.0264	-2.71
one	(dropped)		(dropped)		-1.4901	-0.44	(dropped)		(dropped)		33.844	7.92	39.793	6.33
RMSE	0.0083		0.0117		0.0244		0.0103		0.0357		0.1130		0.0264	
"R-sq"	0.9976		0.9940		0.9911		0.9985		0.9732		0.1574		0.9892	
D-W	1.0050		1.2788		0.9484		0.6292		0.6299		0.2650		0.7905	

3.5 Conclusions

In this article, we provided a new estimation of capital-energy substitution for the manufacturing sector in seven OECD countries. The aim was to examine the nature of the long-run relationship between energy and capital in aggregate manufacturing. We did this using a four-input translog cost function which included input-specific returns to scale (RTS) and technical change (TC) parameters to encompass different production structures. Our estimates show that the technology of the manufacturing sector is mainly characterized by a complementary (or weak substitutability) relation between energy and capital. Constrained model estimates and Morishima substitution measures indicate that limited energy-capital substitution is possible in Germany, Italy and Japan. Caution about the interpretation of results is needed, though, as simplifying hypotheses are involved and the Hessian is not negative definite for all countries and years. Nevertheless, our analysis suggest that in the countries under scrutiny, there might be a quite strong reliance of manufacturing on energy. This finding contrasts with the well-known decoupling hypothesis and idea of green growth (OECD 2011). Indeed, capital-energy complementarity (or weak substitution) means that if energy prices go up capital use goes down, which is likely to result in a lower output in the manufacturing sector. This is not good news for public policy responses to increasing fossil fuel scarcity and climate change: economies are rigid and fragile as production relies, more perhaps than many think, on cheap energy.

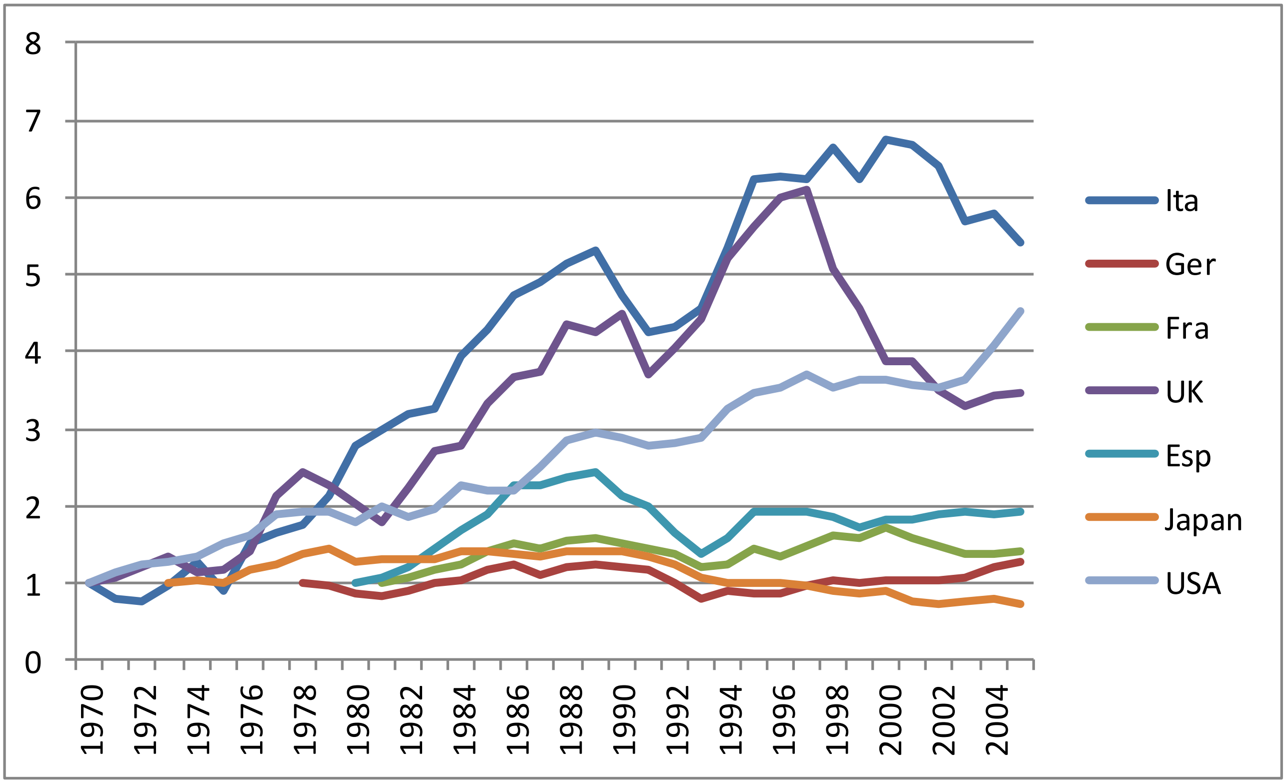
There is a growing support for developing renewable energy options as a solution to both fossil energy scarcity and climate change. However, increasing the share of renewable energy in total energy provision might shape a world of less available and more expensive energy, mainly because of a considerably lower energy return on energy investment (EROI) for renewable sources than for conventional fossil fuels (Hall et al. 2014; Murphy and Hall. 2010). Our findings suggest that a smooth transition from fossil fuels to renewable energy sources might not be easily accomplished: a sustainability transition will require a deep restructuring of OECD economies to reach considerably lower energy intensities of production. This involves the application of more energy-efficient technologies, input substitution and sectoral and demand changes. Energy intensive activities may have to be reduced in volume even.

A steady policy focus on lowering net energy consumption might be needed, both on a national and per capita basis, through climate energy policies within the context of an international climate agreement—which assures that all energy-intensive goods and services provide adequate signals to agents so that energy rebound and carbon leakage are minimized. This “deep restructuring” will particularly affect activities like consumer electronics, plastics, aluminum, cement and glass production and—not to forget—transport, and likely increase the prices of their products and services.

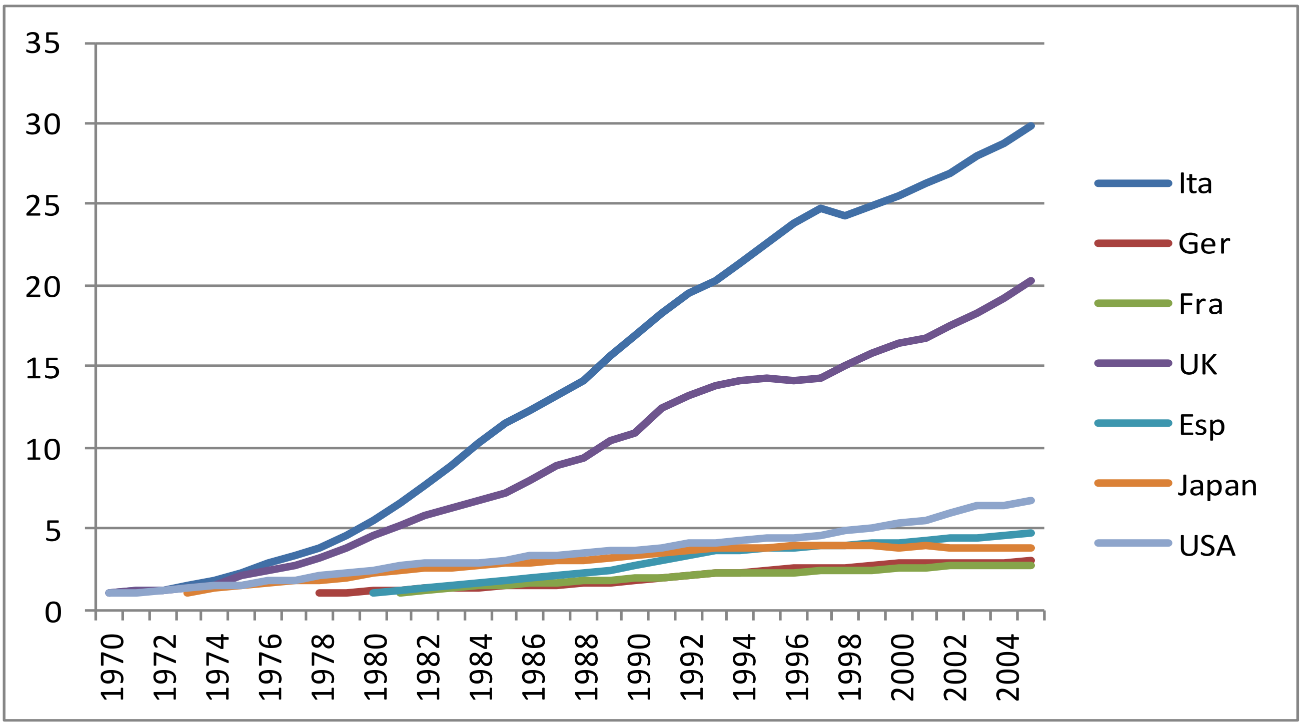
Annex 3.1 Input prices over time (EU-KLEMS)

Note: Starting years are France: 1981, Spain: 1980, Germany: 1978, Japan: 1973, Italy, UK and USA: 1970

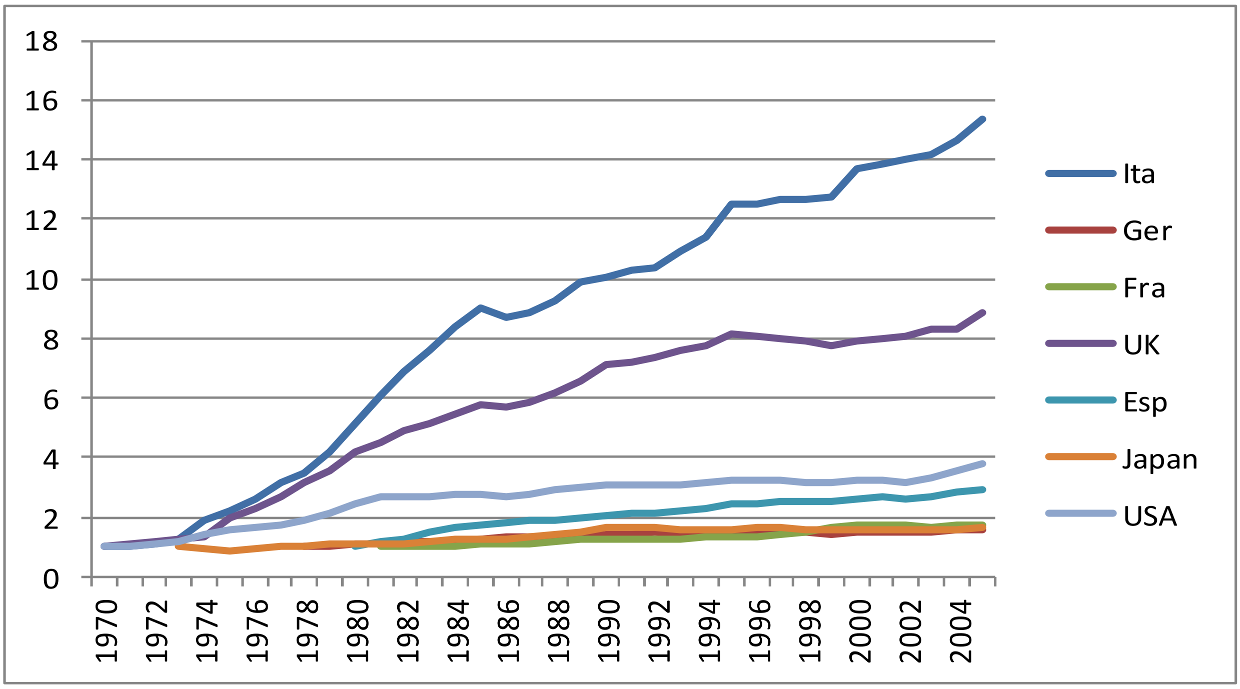
Price of capital



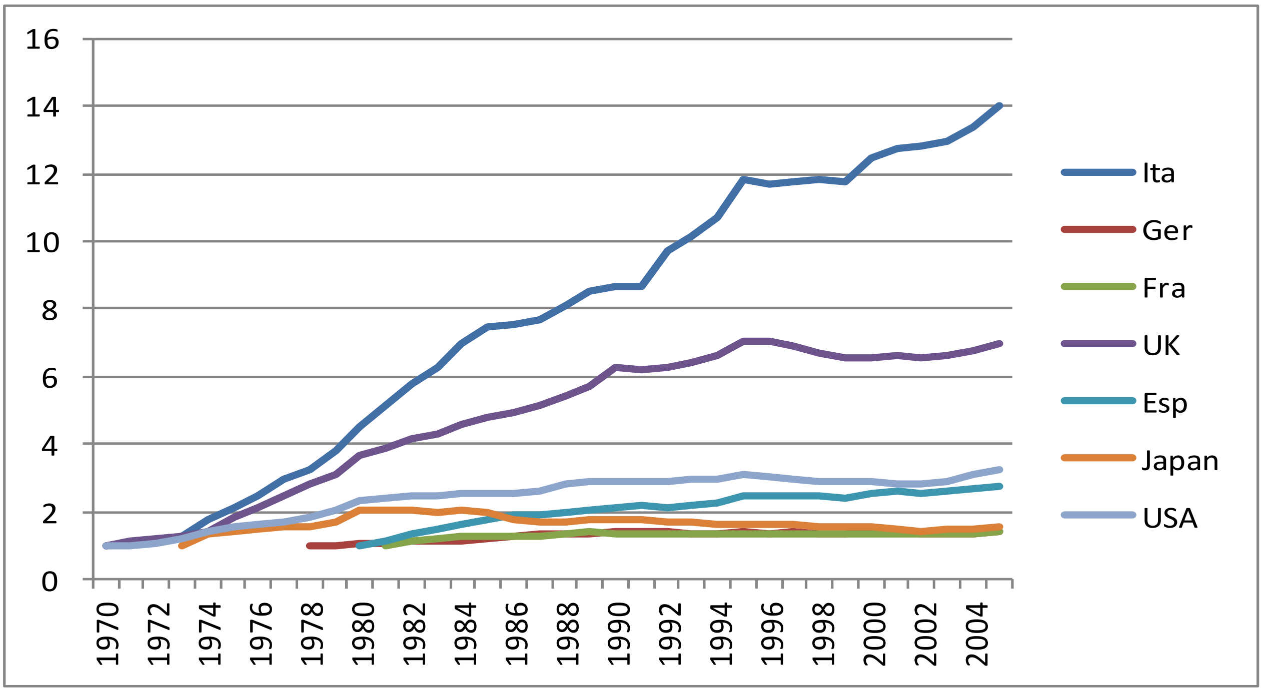
Price of labour



Price of energy



Price of materials



Annex 3.2 EU-KLEMS Input shares

	France				**Germany**				**Italy**				**Japan**				**Spain**				**UK**				**USA**			
	sk	sl	se	sm	sk	sl	se	sm	sk	sl	se	sm	sk	sl	se	sm	sk	sl	se	sm	sk	sl	se	sm	sk	sl	se	sm
1970									0.05	0.44	0.09	0.42									0.06	0.49	0.03	0.42	0.10	0.40	0.08	0.42
1971									0.04	0.46	0.09	0.41									0.06	0.46	0.07	0.41	0.11	0.40	0.08	0.41
1972									0.04	0.46	0.09	0.41									0.07	0.46	0.07	0.41	0.11	0.39	0.07	0.42
1973									0.04	0.45	0.09	0.42	0.10	0.37	0.03	0.50					0.06	0.43	0.09	0.42	0.11	0.39	0.07	0.43
1974									0.05	0.42	0.10	0.43	0.09	0.37	0.02	0.52					0.05	0.42	0.12	0.41	0.10	0.38	0.07	0.45
1975									0.03	0.45	0.10	0.42	0.09	0.40	0.02	0.49					0.04	0.44	0.10	0.41	0.12	0.37	0.08	0.43
1976									0.04	0.44	0.10	0.42	0.09	0.39	0.01	0.50					0.04	0.43	0.12	0.40	0.12	0.38	0.08	0.43
1977									0.04	0.44	0.09	0.42	0.09	0.39	0.02	0.49					0.06	0.42	0.10	0.42	0.12	0.37	0.08	0.43
1978					0.06	0.47	0.06	0.41	0.04	0.44	0.09	0.43	0.10	0.40	0.02	0.48					0.06	0.42	0.12	0.41	0.12	0.38	0.07	0.43
1979					0.05	0.47	0.06	0.42	0.04	0.43	0.09	0.44	0.10	0.38	0.02	0.50					0.05	0.46	0.06	0.42	0.11	0.39	0.08	0.43
1980					0.05	0.47	0.06	0.42	0.05	0.42	0.08	0.45	0.08	0.39	0.02	0.52	0.10	0.29	0.08	0.52	0.05	0.48	0.07	0.41	0.10	0.39	0.09	0.42
1981	0.08	0.35	0.06	0.50	0.04	0.47	0.07	0.42	0.05	0.42	0.08	0.45	0.08	0.40	0.02	0.50	0.10	0.29	0.08	0.54	0.04	0.50	0.05	0.41	0.11	0.40	0.08	0.42
1982	0.08	0.36	0.05	0.51	0.05	0.47	0.07	0.42	0.05	0.43	0.07	0.45	0.08	0.41	0.02	0.49	0.10	0.28	0.09	0.54	0.05	0.49	0.04	0.42	0.11	0.40	0.08	0.41
1983	0.09	0.36	0.05	0.51	0.05	0.46	0.07	0.42	0.04	0.44	0.07	0.45	0.08	0.43	0.02	0.48	0.10	0.27	0.08	0.55	0.06	0.48	0.06	0.40	0.11	0.39	0.07	0.43
1984	0.08	0.35	0.05	0.51	0.05	0.46	0.07	0.42	0.05	0.42	0.06	0.47	0.08	0.42	0.02	0.48	0.10	0.25	0.08	0.56	0.06	0.48	0.05	0.41	0.12	0.39	0.07	0.42
1985	0.09	0.35	0.05	0.51	0.06	0.46	0.07	0.42	0.05	0.42	0.06	0.47	0.08	0.43	0.02	0.47	0.11	0.25	0.08	0.57	0.06	0.48	0.05	0.41	0.12	0.40	0.07	0.41
1986	0.10	0.35	0.04	0.50	0.06	0.47	0.05	0.41	0.05	0.43	0.06	0.46	0.09	0.45	0.02	0.44	0.13	0.26	0.06	0.55	0.07	0.49	0.07	0.38	0.12	0.42	0.06	0.40
1987	0.10	0.36	0.04	0.51	0.06	0.48	0.06	0.40	0.05	0.43	0.05	0.47	0.09	0.47	0.02	0.43	0.12	0.27	0.06	0.55	0.07	0.51	0.05	0.38	0.13	0.40	0.06	0.41
1988	0.10	0.34	0.04	0.51	0.06	0.48	0.06	0.40	0.05	0.42	0.05	0.48	0.09	0.46	0.02	0.43	0.13	0.27	0.05	0.56	0.07	0.49	0.05	0.38	0.14	0.39	0.06	0.41
1989	0.10	0.34	0.04	0.52	0.06	0.47	0.06	0.41	0.05	0.42	0.05	0.48	0.09	0.45	0.02	0.44	0.12	0.27	0.05	0.55	0.07	0.51	0.05	0.37	0.14	0.40	0.06	0.41
1990	0.10	0.35	0.04	0.51	0.06	0.48	0.06	0.41	0.04	0.43	0.05	0.47	0.09	0.43	0.02	0.46	0.11	0.29	0.05	0.54	0.07	0.51	0.05	0.37	0.14	0.40	0.07	0.40
1991	0.10	0.35	0.04	0.51	0.06	0.48	0.06	0.41	0.04	0.46	0.05	0.45	0.09	0.43	0.02	0.45	0.10	0.31	0.05	0.54	0.06	0.51	0.05	0.38	0.14	0.40	0.06	0.40
1992	0.09	0.36	0.04	0.50	0.05	0.50	0.05	0.40	0.04	0.44	0.05	0.47	0.09	0.45	0.02	0.44	0.09	0.33	0.05	0.53	0.06	0.49	0.04	0.41	0.14	0.40	0.06	0.40
1993	0.08	0.38	0.05	0.49	0.04	0.52	0.05	0.39	0.04	0.44	0.05	0.46	0.09	0.46	0.02	0.43	0.08	0.35	0.05	0.52	0.07	0.48	0.04	0.41	0.14	0.40	0.05	0.41
1994	0.09	0.36	0.05	0.50	0.05	0.51	0.04	0.40	0.04	0.42	0.05	0.49	0.09	0.47	0.02	0.42	0.08	0.32	0.05	0.54	0.07	0.46	0.04	0.42	0.15	0.39	0.05	0.41
1995	0.09	0.35	0.05	0.51	0.04	0.50	0.05	0.41	0.05	0.38	0.05	0.52	0.09	0.46	0.02	0.42	0.10	0.32	0.06	0.52	0.08	0.45	0.05	0.43	0.15	0.38	0.05	0.42
1996	0.09	0.36	0.05	0.51	0.04	0.50	0.04	0.41	0.05	0.40	0.05	0.50	0.09	0.46	0.02	0.42	0.10	0.32	0.06	0.52	0.08	0.44	0.05	0.43	0.16	0.38	0.05	0.42
1997	0.09	0.35	0.05	0.51	0.05	0.49	0.04	0.42	0.05	0.40	0.05	0.51	0.09	0.46	0.02	0.43	0.09	0.33	0.06	0.52	0.08	0.44	0.05	0.42	0.16	0.38	0.05	0.41
1998	0.10	0.33	0.05	0.51	0.05	0.48	0.04	0.43	0.05	0.39	0.05	0.51	0.09	0.47	0.02	0.42	0.09	0.33	0.05	0.53	0.07	0.47	0.04	0.41	0.16	0.39	0.04	0.41
1999	0.10	0.33	0.05	0.52	0.05	0.48	0.04	0.43	0.05	0.39	0.05	0.52	0.09	0.47	0.02	0.41	0.09	0.33	0.06	0.53	0.07	0.49	0.05	0.40	0.16	0.39	0.05	0.41
2000	0.10	0.31	0.05	0.53	0.05	0.46	0.04	0.45	0.05	0.37	0.05	0.53	0.09	0.46	0.02	0.43	0.08	0.31	0.08	0.53	0.06	0.49	0.05	0.40	0.16	0.38	0.05	0.41
2001	0.10	0.32	0.05	0.54	0.05	0.46	0.03	0.46	0.05	0.37	0.05	0.53	0.08	0.46	0.02	0.43	0.08	0.31	0.07	0.53	0.06	0.49	0.04	0.41	0.16	0.39	0.05	0.40
2002	0.09	0.33	0.05	0.53	0.05	0.47	0.04	0.44	0.05	0.38	0.05	0.53	0.09	0.46	0.03	0.43	0.09	0.32	0.07	0.52	0.05	0.50	0.05	0.40	0.17	0.40	0.05	0.39
2003	0.09	0.34	0.05	0.53	0.05	0.46	0.04	0.44	0.04	0.38	0.05	0.52	0.09	0.45	0.02	0.44	0.09	0.32	0.07	0.52	0.05	0.50	0.05	0.40	0.17	0.40	0.04	0.39
2004	0.08	0.33	0.05	0.53	0.06	0.44	0.04	0.46	0.04	0.38	0.05	0.53	0.10	0.43	0.02	0.45	0.08	0.31	0.08	0.53	0.05	0.49	0.05	0.40	0.18	0.38	0.05	0.39
2005	0.09	0.32	0.05	0.54	0.06	0.43	0.04	0.48	0.04	0.38	0.06	0.53	0.09	0.42	0.02	0.47	0.08	0.30	0.10	0.52	0.05	0.50	0.05	0.40	0.18	0.38	0.05	0.39
Mean	**0.09**	**0.34**	**0.05**	**0.52**	**0.05**	**0.47**	**0.05**	**0.42**	**0.04**	**0.42**	**0.07**	**0.47**	**0.09**	**0.43**	**0.02**	**0.46**	**0.10**	**0.30**	**0.07**	**0.54**	**0.06**	**0.47**	**0.06**	**0.41**	**0.13**	**0.39**	**0.06**	**0.41**

Note: sx: input share of input x, with x = k, l, e, m.

4 The potential role of a carbon tax in the Italian transport sector[19]

4.1 Introduction

In recent years, while the production and use of stationary energy became cleaner, thanks to more efficient technologies, greener fuels and renewable power, the movement of people and goods did not shift away from asphalt, tires, internal combustion engines and oil products.

The International Energy Agency (2015, p. 19) data on CO_2 transport-related emissions confirm the trend on the rise, with road transport having the lion's share. There are three main reasons for this: i) today's vehicles are heavier and more sophisticated (e.g. with air-conditioning, air-bags, and various electronics) while they mostly run on traditional fuels such as gasoline and diesel; ii) people drives longer routes since the growing size of cities has increased the distance between home and work; iii) goods are mainly transported by diesel road vehicles (≈ 95% share in Italy) over ever longer distances because of an increasing distance between production and consumption.

Within the EU, Italy is a highly-motorized country (Eurostat 2012), characterized by an oversized and obsolescent refuelling network, and a considerable number of cars running on alternative fuels, mainly methane and liquefied petroleum gas (LPG); the latter showing a significant increase in the recent years, due to economic and environmental reasons. So far, there has been no econometric analysis of alternative fuel demand and on the impact of carbon taxes in Italy. To fill this gap and answer the research question *What would be the effect of a carbon tax on fuels on CO_2 emissions?* I estimate both traditional (gasoline and diesel) and alternative (LPG and methane) fuels demands. At this purpose, after assembling an original 3 year dataset with vehicles, fuel prices and quantities at the level of the 110 Italian provinces, including socio-economic indicators as population, income and gas station spatial density, I use the estimated price elasticities to simulate the effect of a 30, 50 and 125 €/ton CO_2, carbon tax. The purpose of this research is to

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highlight the outcomes of a possible strong environmental policy on fuel demand at the local level, introducing a crossed effect variable in the model specification which captures the substitution of ecological for traditional fuels from the tax-induced price differentials.

4.2 Fuel demand, elasticities and carbon pricing

Motor fuel demand has been subject to econometric study for decades. Hundreds of scientific papers have tried to estimate or forecast economic and environmental variables like fuel consumption and composition, tax revenues, or local and global emissions (see e.g. Houthakker et al. 1974, Dahl 1979, Wheaton 1982, Koshal et al. 2007, Davis and Kilian 2011). In some cases, fuel substitution is examined, such as replacing gasoline by diesel or alcohol in Brazil (Alves et al. 2003).

Most functional forms of fuel demand define its quantity as a function of fuel price, income, vehicle stock and additional variables, such as population and infrastructure measures. Studies tend to focus on assessing an elasticity. Price elasticity, in particular, can be derived from both static and dynamic demand equations, including lagged variables. The type of data used influences the elasticity estimates. The data can be in the form of time series (one country, many years, reflecting the evolution of demand), cross-section (one year, many countries, reproducing demand variation in space), or both. Short term effect can be due to less driving while long term effects follow from more efficient vehicles or a modal shift. For a review, see Dahl (2012) and Sterner (2006).

Elasticities from static models typically fall in between short and long run elasticities estimated with dynamic models. Dahl reports for Italy a price elasticity of -0.38 for Gasoline and -0.24 for diesel, a value in the range as found for other EU countries. The meta-analysis by Sterner of dynamic models of gasoline demand reports for Italy a price elasticity between -0.7 and -1.2, and an income elasticity between 0.9 - 1.3.

Fuel price volatility is another important factor for demand estimation. Lin and Prince (2013) estimated a gasoline demand specification which included the price variance as variable, finding that a high variance of the fuel price goes along with lower gasoline consumption, and that the price elasticity is reduced when variance is medium or high. According to Kwon and Lee (2014) highway travel demand shows an asymmetric response to fuel price volatility. The reason is that price uncertainty lowers the impact of a price increase on traffic volume.

Concerning the means to control carbon emissions, carbon pricing can be applied either via cap-and-trade or a carbon tax. In the former case the price is set indirectly by the overall amount of carbon and tradable permits for producers (oil and energy companies, etc.), while in the latter case, the price is set directly by the regulating authority. In both cases, a price effect per volume will differ between fuels, with high-carbon content fuels showing a larger effect. The European Union introduced an Emission Trading Scheme (ETS) in 2005 but excluded road transport from this. While it has set instead an efficiency target for vehicles with the primary goal to reduce average emissions per vehicle, the impact of this on total road transport emissions has been very limited (Desbarats 2009). Some Scandinavian countries adopted a carbon tax in the early 90's to more effectively tackle road transport emissions.

The CO_2 content for gasoline, diesel, LPG and natural gas and the additional cost per liter deriving from a 30, 50 and 125 € per tonne of CO_2 are given in Table 4.1.

Table 4.1 Motor fuel carbon content and additional cost due to carbon tax

Fuel	Unitary CO_2 emissions (kg CO_2/kg fuel.)	kg/liter	Carbon Tax (€/tonne CO_2) 30	50	125
			Additional fuel cost (€/lt.)		
Gasoline	3.2	0.755	0.0728	0.1214	0.3035
Diesel	3.6	0.845	0.0902	0.1503	0.3757
LPG	2.9	0.52	0.0457	0.0761	0.1903
Natural gas (€/kg)	3.1	1	0.084*	0.14*	0.35*

Source: Author's elaboration from IPCC (2006)

4.3. Data and model

We assembled an original database with yearly information for the Italian provinces, including fuel prices, fuel quantities and number of fuel stations. Price data come from Osservatorio Carburanti (or Fuel Price Observatory), a web platform developed by the Ministry of Economic Development (MISE), to increase transparency for consumers and competition within the fuel distibution sector[20]; other variables are the number of vehicles by fuel (cars, industrial vehicles, motorcycles, and buses) from Automobile Club Italia (ACI), the gross income from Ministry of Economics and Finance (MEF), while the natural gas quantities are obtained from Servizi Fondo Bombole Metano (SFBM). Data on province surface and resident population are obtained from Istituto Nazionale di Statistica

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[20] Since 2013, the Italian "Price Transparency Law" (Legge n. 99, 2009, Art. 51) requires compulsory communication of fuel prices from every road fuel retailer to MISE. The price communication must be in real time in the case of an increase and within a week if stable or decreasing . The Observatory information includes all motor fuels (gasoline, diesel, LPG, natural gas and special fuels) allowing detailed spatial analysis as well as pricing behaviour of the fuel retail sector (see Fiorito and Borghi, 2017).

(ISTAT) to derive per capita and density variables.[21] The provinces for which fuel quantity were not available are obviously excluded from the analysis[22].

In assembling the data we were faced with the limitation of having yearly fuel quantities: while prices (from the Observatory) could have been weekly or monthly, enabling the assessment of within-year (or seasonal) price variations, unfortunately the information on fuel consumption has begun to be released on a monthly basis only since 2015, only enabling a yearly frequency. Monthly data are often used in error correction model (ECM) to estimate the eventual asymmetries in fuel demand responses to price variations. The results diverge as asymmetry is found, for example in Sentenac-Chemin (2012) and Chi (2016), or absent as in Bachmeier and Griffin (2003).

The aggregated yearly national quantities and prices are plotted in *Figure 4.1*: it shows that both gasoline and diesel consumption have stagnated during the period of analysis; in 2015 Italy consumed 8 Mtonnes of gasoline, 23 Mt of diesel and 1.6 Mt of LPG, together with about 1 Million cubic meters of natural gas for transport.

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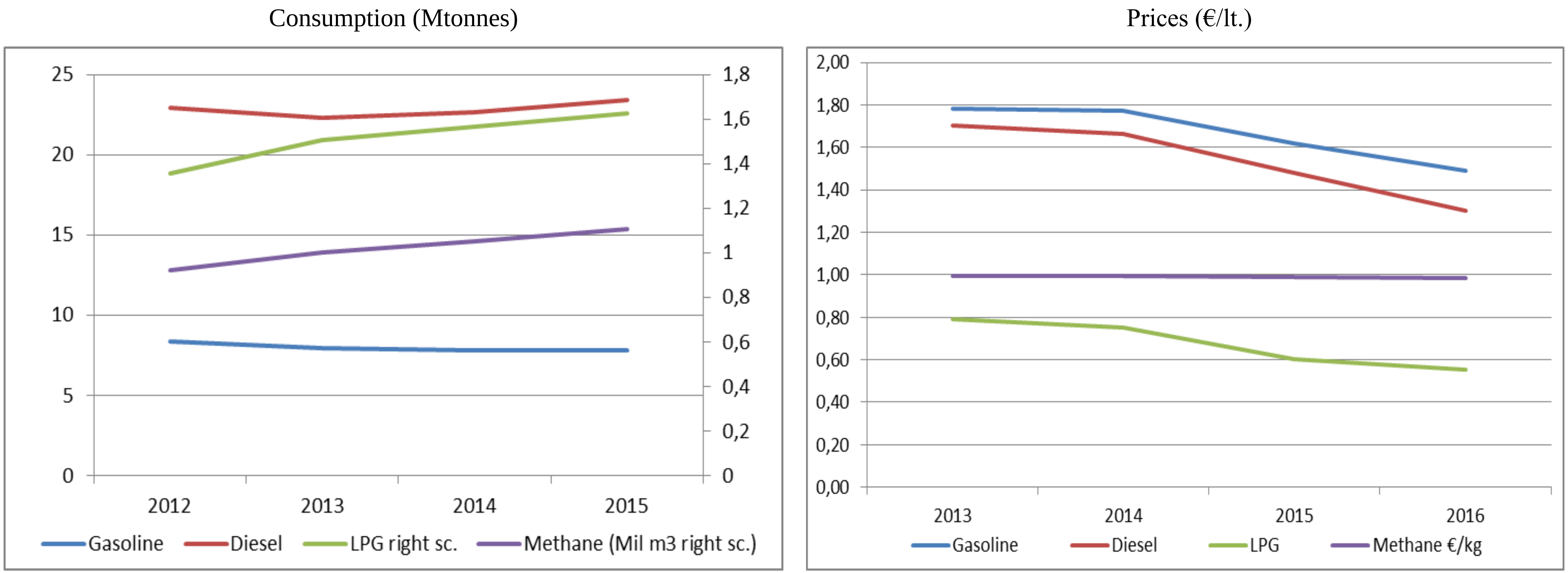
[21] The database and the estimation procedures, written in R software, can be accessed at https://goo.gl/rSn5A7

[22] The fuel quantities for the newly-created provinces of Barletta-Andria-Trani, Carbonia-Iglesias, Fermo, Medio Campidano, Monza e della Brianza, Ogliastra, Olbia-Tempio were not available; LPG is not available in Enna province; Natural gas is available in 101 provinces (not in Sardinia) by approximately 1000 retailers.

Figure 4.1 Motor fuel consumption and prices in Italy



Consumption (Mtonnes)

Prices (€/lt.)

Source: MISE, SFBM

Fuel demand can be expressed as a function of fuel price, income and vehicles running on each fuel. The availability of a fuel is captured by the variable station density *Sijt* expressing the density of refueling stations in units per square km. This variable is motivated by the small number of refueling points for LPG and natural gas. Worthy of note is that model choice was conditioned by the limited period of time for which data were available (2013-2015) explaining why we could not include lagged variables in the demand specification, resulting in a dynamic model. We thus estimate the static panel model (1) with fuel demand variables expressed in logarithms. The advantage of this specification is that elasticities are expressed directly by the estimated parameters. The demand function can be written as:

$$lnF_{ijt} = \beta_{0ij} + \beta_{1i}lnP_{ijt} + \beta_{2i}\, lnY_{ijt} + \beta_{3}iln\, V_{ijt} + \beta_{3i}\, S_{ijt} + e_{ijt} \qquad (1)$$

where,

F_{ijt} : yearly fuel consumption measured in million liters

Y_{ijt} : yearly gross income in €

P_{ijt} : yearly fuel price € per liter

V_{ijt} : vehicles running on fuel i in province j

S_{ijt} : fuel i refueling stations per square km in province j

e_{ijt} : random residual

i : gasoline, diesel, LPG, natural gas

j: province

t : 2013, 2014, 2015.

4.4 Results

We estimate model (1) by ordinary least squares[23]. Several specifications have been tested to explain the quantities demanded, like motorcycles for gasoline, industrial vehicles for LPG and diesel, buses for diesel, population, etc., and inclusion of relative fuel prices (*e.g.* gasoline relative to LPG or diesel relative to natural gas price). After this process of specification selection, one best model specification for each fuel was retained, on the basis of the expected sign of the parameters, their significance and the goodness of fit (R^2). A synthesis of results is in *Table 4.2,* while the complete regression output is reported in *Annex 4.1*.

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[23] In the calculations the yearly quantities of gasoline, diesel and LPG are divided by the factors 738, 829, 550 in order to convert them from tonnes to liters; natural gas cubic meters are divided by 656 to obtain tonnes.

The four specifications produce a satisfactory R^2. The price elasticities have the correct negative sign and are significant with the exception of natural gas. This can be explained by the fact that the price of natural gas has not changed over time and so it does not determine the quantities consumed in the Italian provinces[24]. This result suggests that, for natural gas demand, the number of vehicles and their use are more relevant variables to explain its consumption.

Gasoline, diesel and LPG price elasticities are -0.989, -1.042 and -1.282, respectively, indicating a strong responsiveness in case of price variation. This result is in line with previous evidence based on time series data which reflects short-term price effects to be smaller in magnitude than those based on cross section information that reflect long-term equilibria (Baltagi and Griffin 1984, Pesaran and Smith 1995).

LPG, an alternative fuel, turns out to be sensitive to its availability, as indicated by the station density highly-significant coefficient. This confirms the findings of previous studies on the importance of fuel availability for the demand for alternative fuel vehicles (Achtnicht et al. 2012).

Table 4.2 Demand model estimates for the four fuels

Coefficient	Gasoline	Diesel	LPG	Natural gas
Price	-0.989 *	-1.042 **	-1.282 **	-0.155
Income p.c.	0.356 ***	0.411 ***	-1.172 ***	0.387 ***
Number of private vehicles	0.940 ***	0.813 ***	0.277 ***	0.992 ***
Number of motorcycles	0.080			
Number of industrial Vehicles		0.213	0.784 ***	
Price relative to LPG	-0.672 ***	-1.022 ***		
Price gasoline to natural gas			2.654 ***	
Station density			0.257 ***	
R^2	0.922	0.868	0.685	0.924
Adj. R^2	0.904	0.851	0.667	0.910

Note: ***, ** and * denote significance at 0.1%, 1% and 5% levels.

The coefficient of *Income per capita* is highly significant overall and negative for LPG, a result indicating that LPG vehicles are attractive for low income provinces; for the other fuels income is directly related to fuel consumption, as expected. The *Number of private vehicles* by fuel is also very significant with the sign expected. The variables *Number of motorcycles* is significant for gasoline, and *Number of industrial vehicles* for diesel and LPG equation. The variable *Price*

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[24] The typical supply contract between the natural gas fuel retailers and the gas distributor has a duration of a year, contributing to a rather stable purchase price.

relative to LPG is very significant for both gasoline and diesel; it captures the substitution effect induced by the fuel economy provided by the gaseous fuel. The variable *Price gasoline relative to natural gas* introduced in the LPG equation is positive and significant, which means that if the price of natural gas decreases relative to that of gasoline, LPG demand goes down, indicating an LPG/natural gas substitution effect.

The results indicate a high substitutability between gasoline and LPG on the one hand, and diesel and LPG on the other. This suggests that carbon pricing can make a difference in fuel choices and CO_2 resulting emissions.

Other factors which characterize our estimations, and which limit comparability with other fuel demand studies, relate to the cross-section nature of the data we use. The database used has 110 provinces, meaning high heterogeneity of fuel demand across the country. A logical consequence being that our analysis is better at explaining differences in demand across provinces, using relevant variation in income and vehicle stock, than fuel/vehicle choices determined by price variation over time. Our results should be interpreted in light of the significant heterogeneity of a panel dataset at the province level: in this sense our estimates cannot be compared with those obtained using time series (e.g. Baranzini and Weber 2015, Liu 2015). In particular, we find that both price variability and fuel availability are extreme for LPG and natural gas fuels, as shown by maps of price distribution and the number of fuel stations (Annex 2). These factors become more extreme in the case of natural gas whose regional price ranges from 0.92 to 1.2 €/kg.

A final remark on gaseous fuel availability is in order. At present LPG and natural gas refueling requires the presence of an operator for security reasons. A law allowing for self-service fuel stations with LPG and natural gas is currently under discussion. Its approval will lower distribution costs, increase LPG and natural gas availability and make drivers' life easier. This can contribute to a shift to LPG and natural gas.

4.5. Carbon tax

Already Pearce (1991) recognized the double advantages of carbon taxes: low compliance costs, and a permanent incentive to switch to low carbon energy sources. Here we simulate the effect of a carbon tax on the Italian car fuel market valued 30, 50 and 125 €/tonne CO_2. To quantify the impact of a carbon tax on demand we start from the standard elasticity formula:

$$e = \frac{\Delta q}{\Delta p} * \frac{p}{q}$$

We use this to derive fuel quantity reduction as follows:

$$\Delta q = \frac{\Delta p}{p} q * e$$

From the carbon content of the fuels considered (*Table 4.1)* we proceed to calculate the additional cost per liter of fuel due to a 30, 50, 125 €/tonCO_2 carbon tax. The first value represents the lower end of international considered carbon taxes, while the higher end is motivated by a recent meta-analysis of the social cost of carbon (see for example van den Bergh and Botzen, 2014). In *Table 4.3* we report the relative change in fuel prices and the related effect on fuel quantities demanded, while the details of the emission reductions for the three carbon taxes are presented in *Table 4.4*. The lowest carbon tax produces a 9 € cent diesel price increase (+7.5%), resulting in 0.9 Mtonne fuel reduction (-6.7%) and 3.1 Mtonne CO_2 emissions reduction.

Table 4.3. Percentual changes in fuel prices and quantities for three carbon tax levels

	Gasoline	Diesel	LPG	Natural gas
	30 €/tonne CO_2			
price increase	5.2	7.5	8.3	8.4
quantity decrease	-4.7	-6.7	-9.8	-1.3
	50 €/tonne CO_2			
price increase	8.7	12.5	13.8	14.0
quantity decrease	-7.8	-11.2	-16.4	-2.2
	125 €/tonne CO_2			
price increase	21.7	31.3	34.6	35.0
quantity decrease	-19.5	-28.0	-40.9	-5.5

The absolute changes in emissions for the three carbon tax levels in *Table 4.4* show that the magnitude of both gasoline and diesel price elasticity is responsible for important reductions in use of these fuels: implementing a 30€/tonCO_2 carbon tax will reduce CO_2 emissions from gasoline by almost 1 Mtonne, and from diesel by 3.1 Mtonne, whereas those from LPG and natural gas are negligible. In addition, considerably more, namely 19 million tons of CO_2 emissions, could be eliminated with the introduction of a 125 €/tonCO_2 carbon tax. This represents about 20% of CO_2 emissions by road transport in Italy (IEA 2015).

Moreover, there will be a substitution effect induced by the change in relative fuel prices, captured by the variables *Price relative to LPG* (applied to both gasoline and diesel) and the variable *Price gasoline relative to natural gas*. The changes in relative prices, multiplied by the estimated coefficients imply further reductions of gasoline and diesel consumption. In particular, the high relative price coefficient of diesel demand is responsible for a strong reduction in diesel quantities and related emissions, with a simultaneous increase in demand for LPG and natural gas. *Table 4.4* shows the important substitution effect for diesel (-82 Mtonne). Globally, according to the estimated model, there may be a further reduction in CO_2 emissions in the range between 94 and 109 Mtonne, depending on the carbon tax applied.

As a comparison, Tiezzi and Verde (2016), using U.S. Consumer Expenditure Survey quarterly microdata for 2007-2009, obtain a gasoline price elasticity of -0.435 and, applying different carbon taxes ranging from 5 to 15 to 45 $/ton$CO_2$, fuel demand changes with -10%, -20% and -40%, respectively.

Kim et al. (2011) simulate the introduction of a 54, 108 and 215 US$/tonne CO_2 carbon tax, (approximately 50, 100 and 200 €/tonne CO_2 carbon tax), leading to increases in the price of gasoline of 6.9%, 13.8% and 27.7%, respectively; these changes in gasoline price cause a reduction in consumption of 4.3%, 8.8% and 17.5% . In their study the substitution effect (between gasoline and diesel only) leads to an additional 10% reduction of fuel use and emissions. Unexpectedly high result for diesel are found in simulations by Danesin and Linares (2011): with a tax scheme increasing gasoline and diesel prices by 11% and 27% they obtain a fuel reduction of -2.7% for gasoline and -6.2% for diesel, while long run estimates lead to -8.4% reduction for gasoline and -44.9% for diesel change.

A warning is in order here, namely that our estimates are valid locally, i.e. for the present prices and quantities. In this sense the substitution effect is likely to be overestimated, particularly for diesel, the fuel used by most freight transport vehicles, given that associated investment decisions tend to be slow in responding to fuel price signals (Gonzàlez-Marrero et al. 2012).

Table 4.4 Changes in CO_2 emissions for the three carbon tax levels (Mtons)

Carbon Tax	30	50	125
Direct price effect			
Gasoline	-0.9	-1.5	-3.7
Diesel	-3.1	-5.2	-13
LPG	-0.5	-0.8	-2
Natural gas	0	0	0
Total price effect	-4.5	-7.5	-18.7
Substitution effect from changes in price ratio			
Gasoline	-32	-25	-25
Diesel	-103	-82	-84
LPG	18	18	18
Total substitution effect	-117	-116	-113
Total	-121	-123	-131

4.6. Conclusions

In this article I try to explain fuel consumption in Italian provinces and its response to carbon taxation. I estimate a demand model on the basis of a three year data set with detailed information at the province level. This includes the number of vehicle by fuel, personal income and the density of fuel stations as an indicator of the availability of fuels.

The estimation results of the demand equations confirm the relevance of the number of private vehicles and personal income in explaining consumption of all fuels. Fuel price is significant for gasoline, diesel and LPG with estimates quite high in magnitude. The results show a high price elasticity for diesel compared to previous studies. This is explained by the relatively low weight of freight transport in total transport, given that freight transport is a major user of diesel and slowly responds to price signals. The low significance of the demand parameter estimates for natural gas is due to a lack of price variation and refueling infrastructure being very incomplete (see Annex 4.2).

I used estimated price elasticities to simulate the impact of three levels of carbon tax on the consumption of each fuel. The results showing that an important reduction of CO_2 emissions from road transport is possible through a tax on carbon. The leading contribution to emissions reduction comes from the traditional fuels, gasoline and diesel, which for a 50€/tonneCO_2 see their price increase with 12 and 15 €cents, respectively. More robust estimates, particularly concerning the effect of substitution for LPG and natural gas are possible if longer series will be available, but this requires waiting several years. While panel data are typically used for cross-country comparison, we derived price elasticities from province-level information in a model without lags. This is why our estimates cannot be interpreted either as short or as long term estimates (Espey 1998; Sterner 2007). In addition, it should be noted that variables like vehicle stock, personal income and refueling infrastructure are included, providing information about the heterogeneity of socio-economic conditions in the Italian provinces, which may affect differences in driving behaviour.

Italy emitted 95 million tonnes of CO_2 from road transport in 2013 (IEA 2015). We estimate that taxing carbon from motor fuels might yield a reduction between 4.5 and 18.7 million tonnes of CO_2, equivalent to a reduction of 5% and 20% of Italy’s emissions from transport, respectively; additional emissions reduction is due to the substitution of diesel fuel triggered by relative price changes.

The results of this study are characterized by a strong reduction in diesel consumption, partially compensated by an increase in LPG. To allow such a change in reality, however, wide geographical availability of adequate fuel stations offering this latter fuel is essential.

If mobility has to be maintained to a reasonable level, the overall emission reduction will ultimately depend on the possibility of substitution to low carbon fuels, notably LPG and natural gas. A change in their prices relative to those of gasoline and diesel is critical in this respect, supporting the need for some form of carbon pricing. Finally, it should be noted that for the higher tax levels, 50 and especially 125 €, one should expect a stronger, nonlinear effect, as elasticities will underestimate responses to large price changes. In other words, the estimates offered here are likely to represent lower bounds.

Annex 4.1 Estimation results for four fuel demand models

Gasoline

```
     Estimate  Std. Error t-value Pr(>|t|)
(Intercept) -9.175560  0.734116 -12.4988 < 2.2e-16 ***
lb_p    -0.989143  0.415483 -2.3807  0.0179 *
lredimpoPC  0.356198  0.056940  6.2557 1.352e-09 ***
auto     0.940522  0.047252 19.9042 < 2.2e-16 ***
moto     0.080886  0.043412  1.8632  0.0634 .
rel_p_b_lpg -0.672036  0.132863 -5.0581 7.361e-07 ***
Total Sum of Squares:  180.63
Residual Sum of Squares: 14.037
R-Squared:   0.92229
Adj. R-Squared: 0.90432
F-statistic: 716.814 on 5 and 302 DF, p-value: < 2.22e-16
```

Diesel

```
      Estimate Std. Error t-value Pr(>|t|)
(Intercept) -8.127000  0.843696 -9.6326 < 2.2e-16 ***
ld_p    -1.042836  0.372025 -2.8031 0.005388 **
lredimpoPC  0.411422  0.075969 5.4156 1.248e-07 ***
auto     0.813038  0.113538 7.1609 6.137e-12 ***
veic_ind   0.213400  0.121845 1.7514 0.080892 .
rel_p_d_lpg -1.022480  0.228900 -4.4669 1.123e-05 ***
Total Sum of Squares:  170.82
Residual Sum of Squares: 22.455
R-Squared:   0.86855
Adj. R-Squared: 0.85163
F-statistic: 399.08 on 5 and 302 DF, p-value: < 2.22e-16
```

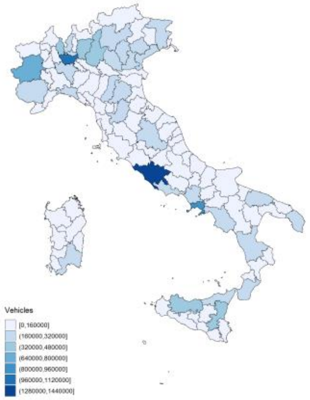
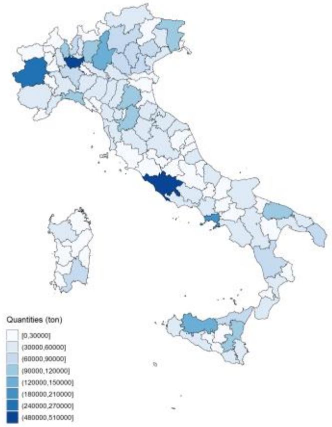
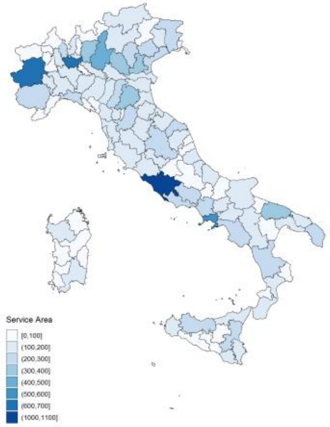
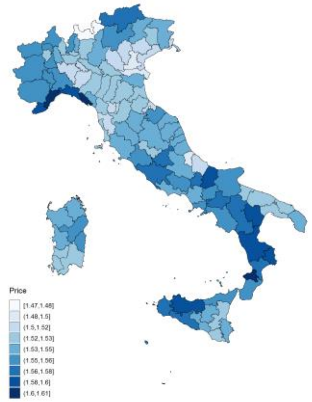
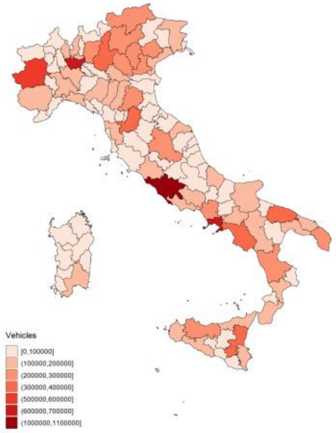
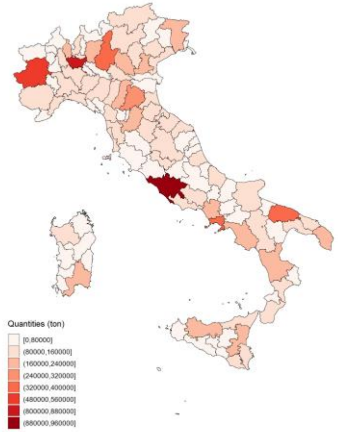
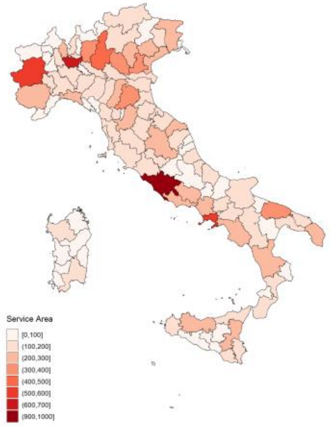
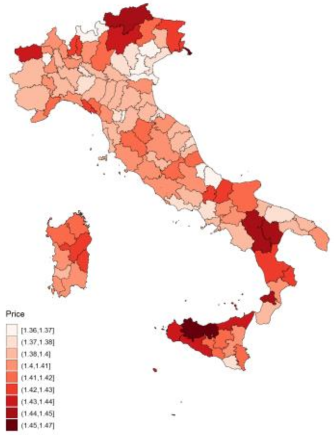
LPG

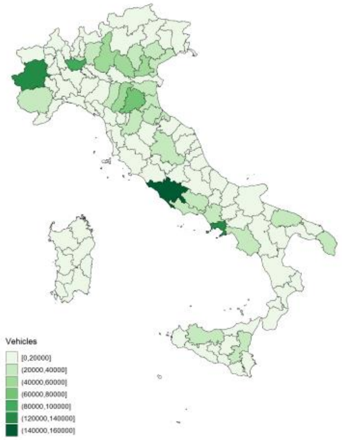
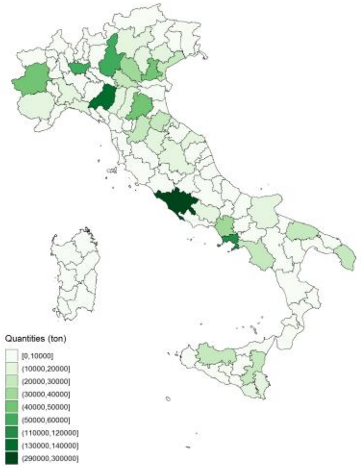
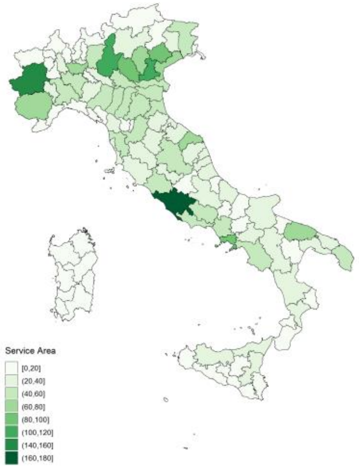
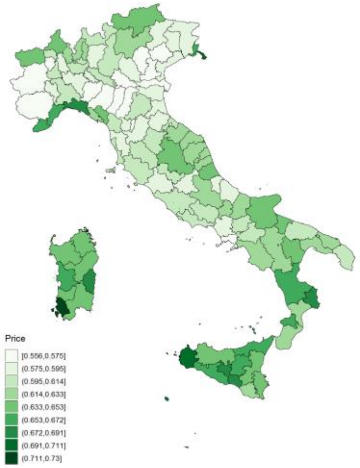
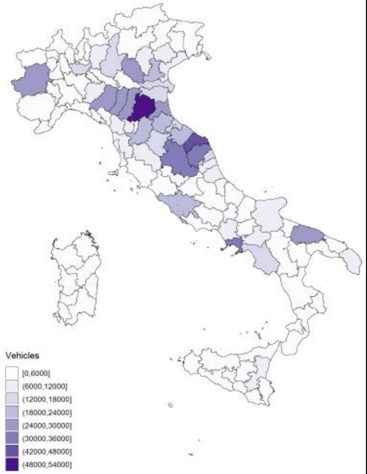
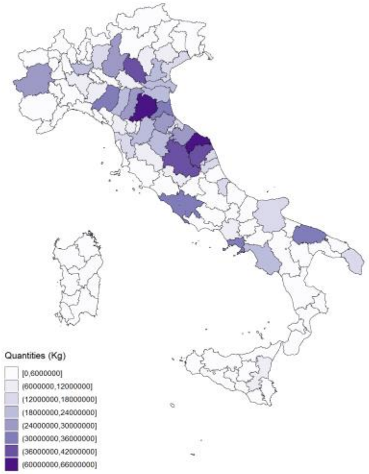
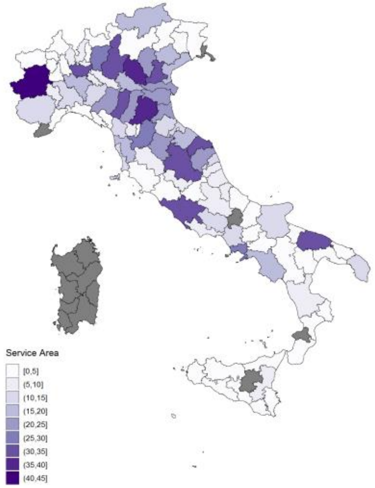
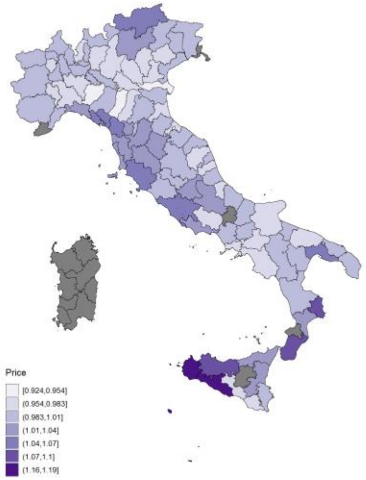
Estimate Std. Error t-value Pr(>|t|)
(Intercept) 2.747171 2.113415 1.2999 0.1947530
llpg_p -1.282026 0.492908 -2.6009 0.0098092 **
lredimpoPC -1.172568 0.199681 -5.8722 1.260e-08 ***
auto 0.277280 0.080380 3.4496 0.0006512 ***
vec_ind 0.784489 0.089252 8.7896 < 2.2e-16 ***
rel_p_b_met 2.654994 0.636128 4.1737 4.046e-05 ***
adsdens 0.257131 0.050270 5.1150 5.958e-07 ***
Total Sum of Squares: 369.56 Residual Sum of Squares: 116.34 R^2R-Squared: 0.6852 Adj. R^2: 0.66789 F-statistic: 97.9498 on 6 and 270 DF, p-value: < 2.22e-16

Natural gas

Estimate Std. Error t-value Pr(>|t|)
(Intercept) -2.988382 0.901728 -3.3141 0.0010429 **
lmet_p -0.155860 0.713951 -0.2183 0.8273521
lredimpoPC 0.387756 0.098654 3.9305 0.0001073 ***
auto 0.992172 0.019358 51.2547 < 2.2e-16 ***
Total Sum of Squares: 477.69 Residual Sum of Squares: 36.218 R-Squared: 0.92418 Adj. R-Squared: 0.91093 F-statistic: 1117.34 on 3 and 275 DF, p-value: < 2.22e-16

Annex 4.2 Province-level maps of four core features of the four fuels in December 2015

	Private Vehicles	Fuel Quantity	Number of Stations	Prices (€/lt.)
Gasoline				
Diesel				

LPG				
Natural gas				

5. Conclusions

This thesis is motivated by the challenges posed by the combination of energy scarcity and climate change. The three articles presented range from production to transport economics, with an environmental angle added; I used graphical, statistical and econometric tools to perform my studies. The motivaton for this was that it allows to systematically address major energy-related environmental questions from an empirical angle, using rigorous statistical-econometric approaches, and presenting results with transparent graphs (including a video).

In the first study I examine the energy-economy connection to see whether a narrow indicator of economic development, GDP, and citizens' final energy consumption show correlated behaviour in the long term. This research question is relevant in light of both post-WW2 energy (growth) policies and 1973/79 oil shocks, and subsequent national energy conservation policies. I assessed the environmental performance of the world economies by studying their energy intensity in the long term. The main findings of this study is that energy intensity is not an adequate indicator, since it hides the dynamics of the variables composing it. This led me to open up the 'black box' of the national economy variables and to work at a (multi-)sectoral scale. In the second study I focus on production by analyzing a critical sector to the economy, namely manufacturing. By assessing the elasticity of substitution of energy and capital inputs one can characterize a country's manufacturing technology. In particular, the possibility to handle a situation of energy price volatility appears to be characterized by uncertainty: economies are rigid since production – so far- has gone along with cheap energy. The previous research is complemented by accounting for a sector with considerable fossil energy consumption, namely transportation. There, carbon pricing il likely to bring significant environmental benefits. Here I summarize the main insights of these three studies and derive general suggestions for policy and future research.

Whether energy intensity is a useful indicator for assessing decoupling is the research question dealt with in Chapter 2. Here I attempt to unfold the semantic problems arising with the indicator EI, the ratio of GDP per capita and energy consumption per capita, which synthesizes into one single figure three fundamental pieces of information: energy, income and population. Its usefulness is questioned by straight visualization. I show how the ratio, i.e. the slope in an opened plane with per capita energy and GDP on the two axes, actually hides the existence of huge differences in the structure of national economies. After dividing the world's countries in three types, namely low, medium and high EI clusters, the graphs show that many countries with extremely different levels of GDP and energy use fall into the same cluster. I also show how energy and GDP are strongly correlated across countries and (with a few exceptions) over time with a correlation coefficient for the former close to 1 ($R^2 \approx 0.97 - 0.99$). Dynamic analysis of changes over time on a video confirm how the transition toward services experienced by most advanced economies has gone along with a shift in production (and pollution) to other countries less developed. This study suggests that to identify the factors determining decoupling, one should move the level of energy intensity analysis from national to sector and include the effect of international trade. Ultimately, in order to study the role played by energy in economic development one needs to develop a more rich and disaggregate analysis than merely observing the ratio of energy consumption to GDP.

The second study in Chapter 3 dealt with the issue of capital-energy substitution in the production function for the manufacturing sector. The question whether energy and capital inputs are substitutable for one another is of paramount importance for environmental and energy policy. By estimating the production function for seven advanced economies, I could examine the resilience of the economic system to higher energy prices, whether due to energy scarcity or stringent climate policies. The results confirmed the existence of a complementarity relation between energy and capital. This means that the manufacturing sector has little flexibility in responding to higher energy prices; energy and capital cannot smoothly substitute for one another and, if energy prices rise, the manufacturing sector will be unable to compensate a more expensive and reduced energy availability by an addition of more capital. The results show that energy-capital complementarity characterizes the technology of the manufacturing sector in France, UK and USA, whereas limited (weak) substitution holds for Germany, Italy and Japan.

The study presented in Chapter 4 focuses on the potential impact of a carbon tax applied to the Italian transport sector. The possible CO_2 emission reduction deriving from taxing carbon in a highly-motorized country is quantified using an econometric model analysis, carried out at the province level, based on a large data set. This territorial detail helps explaining the country's heterogeneity in terms of socio-economic conditions, transport infrastructure and regulatory conditions. A carbon tax is generally considered as an effective means to reduce global emissions of CO_2. It can stimulate a shift from traditional high-carbon to low-carbon fuels. Demand estimates and associated elasticities are derived from demand models for the four main motor fuels, namely gasoline, diesel, LPG and methane. These provide evidence that a carbon tax on motor fuels in Italy may induce a strong switch to alternative fuels such as LPG and methane, enhancing an already ongoing trend. According to this analysis, a carbon tax between 30 and 125 €/tonCO_2 would reduce emissions between 5 and 20% for gasoline and between 7 and 28% for diesel fuel. Nevertheless, such a change will depend on adequate developments of distribution infrastructure: in particular, the number of LPG and methane supply stations must grow, especially in central and southern regions. A positive development is that this change is already happening[25]. The political relevance of this study is that a fiscal measure to internalise the costs of climate change in transport would be a reliable and effective measure to make a transition to a low-carbon economy.

The results of the first two studies in this thesis might disappoint those betting on green growth. First, my global critique of the EI represents a warning for many researchers relying on declining EI over time to develop optimistic forecasts about the sustainability performance in many service-based economies. On the other hand, input substitution has long been considered as a given techno-economic argument favouring optimistic visions about a possible smooth recovery in the case of energy price shocks. In the final study, direct carbon pricing via carbon tax is found to be an effective option for curbing road transport emissions; as indirect carbon pricing via market based mechanism has been the option of choice so far, my work might face resistance from those favouring the cap–and–trade CO_2 control system.

Of course there are various open ends which can motivate further research. The capital-energy substitution analysis can be continued if more updated information becomes available. Notably, the inclusion of post-2009 data would likely provide a better picture of the state of EU/OECD manufacturing sector since the decade is characterized by slow, sometime negative growth, the energy/capital relationship certainly deserves updated estimates. Concerning the contribution on the transport sector, the possibilities offered by alternative fuels, or the adoption of new drivetrains (or prime movers) such as hybrid, full electric or hydrogen fuel-cells deserve more attention in terms of their potential for local and global emissions reductions. Future research might focus on alternative demand models associated with changes in behavioural features of drivers, as consumer demand seems to be highly responsive to fiscal incentives in accordance with the increasing environmental awareness among drivers.

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[25] An agreement between FCA Group, SNAM S.p.A. and IVECO to double the number of natural gas retailers in the next 10 years has been signed on Oct. 6, 2016. http://www.lastampa.it/2016/10/06/motori/ambiente/fca-iveco-snam-accordo-per-promuovere-il-metano-la-rete-di-distribuzione-raddoppier-5JpptotsgaxDJtaXYslHXN/pagina.html

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