

## **Energy Demand and Temperature: A Dynamic Panel Analysis**

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# Energy Demand and Temperature: A Dynamic Panel Analysis

## Summary

This paper is a first attempt to investigate the effect of climate on the demand for different energy vectors from different final users. The ultimate motivation for this is to arrive to a consistent evaluation of the impact of climate change on key consumption goods and primary factors such as energy vectors. This paper addresses these issues by means of a dynamic panel analysis of the demand for coal, gas, electricity, oil and oil products by residential, commercial and industrial users in OECD and (a few) non-OECD countries. It turns out that temperature has a very different influence on the demand of energy vectors as consumption goods and on their demand as primary factors. In general, residential demand responds negatively to temperature increases, while industrial demand is insensitive to temperature increases. As to the service sector, only electricity demand displays a mildly significant negative elasticity to temperature changes.

**Keywords:** Energy Demand, Temperature, Dynamic Panels

**JEL Classification:** C3, Q41, Q54

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## **1. Introduction**

The summer of 2003 will be remembered in Europe for its exceptional heat wave that hit the continent from June to middle August causing more than 30,000 deaths. This was accompanied by a sharp increase in electricity consumption that occasionally resulted in power outages and blackouts<sup>1</sup>.

The summer of 2005, at least in southern Europe, has had hot spells as well, but this time the consequences for the European citizens have been way less dire. The much feared heat wave did not materialise, but, besides this lucky escape, one factor that may have also contributed to seriously reduce the heat stress on the population, is that people seem to have learnt from the past and taken countermeasures. It is interesting to note that these countermeasures should, in principle, affect energy demand. In Italy for instance, the scalding hot last ten days of June 2005 has seen the all time record (up to that day) in electricity consumption, peaking on June 28 at 11.30 a.m. with 54.1 GWh. The most likely direct cause for this increase in electricity consumption seems to be the boom of air conditioners whose sales have increased fivefold in Italy from 2001 to 2004.

In short, it seems that people's reaction to the steady increase in temperatures of the last few years is affecting their energy use patterns. Installing more and more air conditioners is but one facet of the phenomenon. Italy's example is particularly striking, but similar patterns are occurring around the world, with differences as to the pace and timing of the adaptation process.

However, the all time record for electricity consumption was again broken twice in Italy during this exceptionally cold winter, peaking on January 25, 2006, with 55.5 GWh<sup>2</sup>, while gas strategic reserves had to be tapped in February to compensate the reductions in Russian exports.

Thus, the question that arises from this anecdotal evidence is: if take a broader stance and look at the effect of climate on the demand for different energy vectors, from different categories of final users, and over the whole year, how important is climate in explaining energy demand, and in which direction does climate affect it?

This paper addresses these issues by means of a dynamic panel analysis of the demand for coal, gas, electricity, oil and oil products by residential, commercial and industrial users in OECD and (a few) non-OECD countries. The ultimate motivation for investigating these issues is to derive long-run elasticities for temperature, to be used as an input for a consistent evaluation of the impact of climate change on a key class of consumption goods and primary factors such as energy vectors. It turns out that temperature has a very different influence on the demand of energy vectors as

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<sup>1</sup> However in 2003, Italian electricity consumption peaked in December, with 53.4 GWh (GRTN, 2005).

<sup>2</sup> See Terna (2006).

consumption goods and on the demand of energy vectors as primary factors. Residential demand responds negatively to temperature increases, (but this does not happen for all energy vectors), while industrial demand is insensitive to temperature increases. As to the service sector, only electricity demand display a mildly significant negative elasticity to temperature changes.

In the empirical literature on energy demand, temperature is often considered a good candidate for an explanatory variable of energy demand, but it is rarely the focus of analysis. The main exception is the strand of literature that focuses on residential electricity demand, in which phenomena such as the one described in the introduction are of primary relevance. Examples of these kind of studies are Hanley and Peirson (1998) and Taylor and Buizza (2003) on Britain, Giannakopoulos and Psilogou (2004) for Athens, Greece, Al-Zayer and Al Ibrahim (1996) for Saudi Arabia, Pardo et al.(2002) and Valor et al. (2001) for Spain, Sailor (2001) for the US. These studies look at the relationship between daily and seasonal load demand variability and temperature, often expressed in terms of heating and cooling degree days. Given the very short run focus of these studies, their aim is mainly to explain (and often forecast) the variability of electricity demand, rather than estimating demand functions. Economic variables such as prices hardly play a role, except where time–use pricing is enforced (e.g. Hanley and Peirson (1998)).

The study most akin in spirit to our analysis is the one by Amato et al. (2004), which has however a very different geographical focus. By concentrating on the impacts on the residential and commercial energy demand in Massachusetts, the authors are able to employ high quality monthly data. They derive demand elasticities to temperature changes for electricity and heating oil fuels. In a further step of analysis, they compute the impacts of climate change in terms of degree day units variations on the energy vector demands using partial equilibrium simulations based on global climate scenarios. They find notable changes in the overall energy consumption and in the energy mix of the residential and commercial sectors in the region under scrutiny.

Bentzen and Engsted (2001) argue in favour of a rehabilitation of the standard autoregressive distributed lag model (ARDL) in time-series energy demand estimation. Their point is that, although when variables are non-stationary spurious regression and consequently invalid t-and F-tests may results, short and long run parameters can be consistently estimated and valid inference can be made if there is a unique cointegrating relationship between the variables. They compare ARDL to Error Correction Models to Danish energy demand over the period 1960-1996 to find that

they give very similar results. Temperature (in the form of heating degree days) was included and its elasticity found to be negative and significant.

There is quite a number of studies applying cointegration techniques to energy demand. These studies generally focus on a single country or on a restricted group of countries. Glasure and Lee (1997) study the cases of South Korea and Singapore, with no regard to temperature. Their interest lies in finding out the direction of causality between energy demand and GDP growth, which they can determine in the case of Singapore. Similar in spirit are the study by Stern (2000) on the US economy, and Masih and Masih (1996) on South-East Asian economies. In both cases the focus is on the cointegration of GDP and energy use, with particular regard on the direction of the causality of changes in these variables. Silk and Louz (1997) look at US residential electricity demand by means of a micro error correction model of residential demand. Variable used include degree days, disposable income, interest rates electricity and fuel oil prices. Beenstock et al (1999) apply three different estimation procedures (Dynamic Regression Model and OLS and Maximum Likelihood. Cointegration) to Israel industrial and household energy demand. Their explanatory variables include heating and cooling degree days. Their focus however is on the different capabilities of the alternative estimation methods tested to account for seasonality and in particular, seasonal cointegration.

The rest of this paper is organised as follows. The next section describes the dataset used. Section 3 introduces and discusses the methodology used. Section 4 presents the main results and Section 5 concludes.

## **2. Data**

Our study concerns 13 categories of aggregate energy demand, classified by type of energy vector (coal, natural gas, electricity, oil and oil products) and by type of user (households<sup>3</sup>, commercial and industrial demand). For each category a dynamic model has been formulated and estimated, using the following observed variables: Real Gross Domestic Product (RGDP), market price and yearly average temperature, plus the first lag of the demand. Demand and GDP data were taken from Energy Balances and Energy Statistics (IEA); price data were taken from: Energy Price and Taxes, (IEA). Temperature data were derived from the *High Resolution Gridded Dataset*, (Climatic Research Unit University of East Anglia, UK and the Tyndall Centre for Climate Change Research). RGDP is expressed in billion 1995 US dollars, using exchange rates for the industrial sector and using Purchasing Power Parities for households for the household models; in this case

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<sup>3</sup> Household and commercial demands of crude oil are negligible and hence not considered in this study.

RGDP is expressed in per capita terms. Temperatures are expressed in Fahrenheit degrees in order to allow definite logarithm transformations. Demands are expressed in Ktoe, while prices are expressed in real terms, in 1995 US dollars<sup>4</sup>.

For what concerns panel dimensions, the selected collections of data comprise the observations of a varying number of nations along a period of 23 years, from 1978 to 2000. A problem not to be overlooked is the occurrence of missing values, mainly among price data. We had to find a compromise, for each model estimated, between their number and the number of cross sections included in the panel. We followed simple, rough rules: first, we discarded country specific series for which too many observations were missing; second, for the series included in each model's data, we replaced the remaining missing observations series with moving averages of five contiguous years. This results in a varying number of countries included in each model., as shown in table 1. The proportion of missing data filled in for each series using the procedure described above is in any case, negligible. (below 4%). Therefore we expect the corresponding bias to be at most of scarcely significant influence.

### 3. Methodology

#### 3.1 The estimation strategy: GMM estimation of dynamic homogeneous panel data models with unobserved fixed effects

A widely used methodology for dynamic panel modelling applies General Method of Moments (GMM) estimators. The rationale for relying on Generalized Method of Moments techniques is to obtain estimates under fairly general assumptions, using at the same time relatively simple techniques of analysis.

We focus our attention upon the following model:

$$y_{it} = \rho y_{i,t-1} + \mathbf{x}'_{it} \boldsymbol{\beta} + c_i + u_{it} \quad ; \quad i = 1, \dots, N, \quad t = 1, \dots, T \quad (1)$$

where  $c_i$  are the unobserved, specific characteristics of the cross-sections,  $u_{it}$  is the error, and  $\rho y_{i,t-1}$ ,  $\mathbf{x}'_{it} \boldsymbol{\beta}$  is the whole set of regressors; the latter term represents a subset of  $k-1$  generic observed variables:  $x_{it}^{(j)}$  ;  $j=1, \dots, k-1$ . We are dealing with an AR(1) dynamic unobserved effect model,

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<sup>4</sup> Most data were already available at the desired level off sectoral aggregation, except for the prices of some energy vector prices, which we aggregate into more general categories in a preliminary stage. For the coal model for households, we considered only Steam Coal prices, while for the industrial oil products demand model we considered only Automotive Diesel ones. Moreover, the (industrial) demand for crude oil is mostly nought; thus we considered the correspondent entries for Petroleum Refineries.

homogenous in the parameters; throughout the discussion we will always keep the “fixed effects” hypothesis, i.e. the presence of arbitrary correlation among regressors and unobserved effects.

These theoretical assumptions restrict the range of applicable techniques, which mainly have to do with the treatment of asymptotic proprieties in the “large  $N$ , large  $T$ ” case.

Let us reformulate the model (1) in a more useful expression, where all the regressors are grouped together:

$$\begin{aligned} y_{it} &= \mathbf{w}_{it}'\boldsymbol{\gamma} + c_i + u_{it} \quad ; \quad i = 1, \dots, N, \quad t = 1, \dots, T \\ \mathbf{y}_i &= \mathbf{W}_i\boldsymbol{\gamma} + c_i\mathbf{1}_T + \mathbf{u}_i \quad ; \quad i = 1, \dots, N \end{aligned} \quad (2)$$

where  $\mathbf{1}_T$  is the  $T$ -dimensional vector of ones, and:  $\mathbf{y}_i = (y_{i1}, \dots, y_{iT})'$ ,  $\boldsymbol{\gamma} = (\rho, \boldsymbol{\beta}')$ ,  $\mathbf{w}_{it} = (y_{i,t-1}, \mathbf{x}'_{it})'$ ,  $\mathbf{W}_i = (\mathbf{w}_{i1}, \dots, \mathbf{w}_{iT})'$ . One can obtain several estimators from an auxiliary regression, which is derived from the original model by applying the First-Differences operator  $\Delta$ :

$$\Delta\mathbf{y}_i = \Delta\mathbf{W}_i'\boldsymbol{\gamma} + \Delta\mathbf{u}_i \quad ; \quad i = 1, \dots, N \quad (3)$$

This transformation removes the individual effects  $c_i$ ; it also inserts on the right-hand side of (3) a lagged-differenced dependent variable:  $\Delta y_{i,t-1}$ ; which is, by construction, correlated with the error term  $\Delta u_{it}$ . Moreover, since the differenced errors derive from serial uncorrelated ones, it does not necessarily preserve non-correlation among errors<sup>5</sup>. However, from our point of view, these are not serious drawbacks of the method.

This method was originally developed by Anderson and Hsiao (1981,1982), who considered a simple class of dynamic estimators; in particular, they obtained a consistent Instrumental Variables estimator from model (3) with instruments corresponding to the lagged past differences:  $\Delta y_{i,t-2}$ ; or levels:  $y_{i,t-2}$ ; of the original dependent variables. In subsequent works, their strategy has been widely expanded: on one hand, one can obtain GMM estimators by extending the set of instrumental variables employed; on the other hand, much effort has been spent in the research of optimal efficiency, by developing the best set of restrictions connected to the Instrumental Variables (IV) themselves. The most interesting consequence from our point of view is that this approach allows the handling of models with non-exogenous and exogenous regressors (other of lags of the dependent) together, and/or with serially correlated errors (even integrated ones). The latter issues go beyond the scope of this paper<sup>6</sup>.

<sup>5</sup> Unless one resorts to the Forward Orthogonal Deviations operator, developed by Arellano and Bover (1995).

<sup>6</sup> A comprehensive review can be found in Baltagi (1995); chapter 8.

### 3.2 Application to energy demand

*Adopted strategy: advantages and drawbacks.*

The alternative to GMM estimation would have been using panel data cointegration techniques, which are extensively applied in the relevant literature on energy demand estimation. However, this led to a tricky issue, related to the low power of preliminary unit root tests; the results of these tests in our case were hardly decisive. In other words, the low power of the tests performed made it quite likely to incur in a type II error. Therefore we could not safely assume that accepting the null hypothesis of unit roots was justified by the results of the tests<sup>7</sup>.

It was thus decided to resort to Arellano-Bond estimators. This methodology has the following advantages:

- it allows to handle strictly exogenous and predetermined regressors, even if arbitrarily correlated with the unobserved effects;
- it yields robust estimates with respect to serial correlation and heteroskedasticity of errors;
- it does not require any assumption about the initial observations of the dependent variable.

The robustness of estimators is linked to the hypothetical cointegrating relations between the reference variables: in particular, such estimates can be obtained whether the cointegrating relation expressed by our particular model is significant (this implies a stationary error) or not (in this case the error must be integrated).

Recalling the asymptotic results illustrated in the precedent paragraph, in our case the estimates may be biased, since the panel dimensions of the data have the same order. However this drawback is of relative importance, given the purposes of this analysis.

It is also worth noting the effects of sources of bias other than the one mentioned above.

- 1) *Sample bias*. The original series on which our data are based present some incongruities, mostly in the form of more or less extended jumps in trends or in levels<sup>8</sup>. Such occurrences can be considered outliers, and imputable to exogenous events, such as structural changes of economies.
- 2) *Cross-sectional correlation of observations*. This issue implies the violation of one basic assumption of general panel data estimators. In our case it appears to be inherent to the characteristics of the phenomena under scrutiny: in particular, the unit of observations in the panels are countries, mostly OECD, and one can reasonably expect some homogeneity in their macroeconomic trends. More precisely, the observed demands may show a certain similarity in

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<sup>7</sup> For a survey of cointegration issues in panel data, see Banerjee (1999).

<sup>8</sup> For instance, in the case of German households demand of electricity, there is a very wide jump imputable to a change in classification, occurred in 1983. Fortunately in this case correcting the series has been quite straightforward.

behaviour, due either to their mutual relations, or to the influence from common economic events.

These issues were dealt with in the course of a comprehensive data validation stage, using residual analysis techniques. In brief, the effects of sample bias are more easily recognizable: they generate a bias in the estimates and in an increase of their estimated variances and covariances; however they have negligible consequences in presence of a wide number of observations (as in our case). However, we do not know the effects of cross sectional correlation of observations, but after some empirical check, we consider it to prevail over the other one, even if the obtained estimates were considered to be acceptable. This outcome puts evidence, although not always fully statistically significant, in favour of the hypothesis that the global amount of bias is limited<sup>9</sup>.

To summarize, the adopted strategy of estimation is not suitable in all circumstances, and in our case it presents two drawbacks: namely, asymptotic bias and cross-correlation bias. As it will be shown the estimates are however satisfactory for the purposes of the study. Moreover, alternative estimators, such as those illustrated in the preceding paragraph, constitute only a partial remedy, since they are also based on the basic hypothesis of cross-sectional lack of correlation.

It is interesting to note a link between the two drawbacks: the estimators behave optimally in the fixed  $T$ , large  $N$  asymptotic context, that is typical of the studies regarding firms, countries, etc., where there is a great number of available cross-sections (and few periods observed, at least once ago): for this reason it is implicitly assumed that the data comes from a random sample of units of observation; for instance ideally one would have a cross sectional uncorrelated GDP.

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<sup>9</sup> The practical details will be illustrated in the next section.

TABLE 1 ABOUT HERE

### 3.3 Functional form

Since our main interest is to derive long-run elasticities of energy demand to temperature, we focus our attention upon log-log demand models having the following functional form:

$$D_{it} = \beta_0 + \delta t + \rho D_{i,t-1} + \beta_1 Y_{it} + \beta_2 P_{it} + \beta_3 P_{jt} + \beta_4 T_{it} + c_i + u_{it} \quad ; \quad i, j = 1, \dots, N, i \neq j, t = 1, \dots, T \quad (4)$$

where  $D_{it}$  represents the logarithm of the demand, while  $Y_{it}$ ,  $P_{it}$ ,  $P_{jt}$  and  $T_{it}$  stand for the logs of RGDP, end-user prices (for the energy vector under scrutiny and for alternative fuels when relevant<sup>10</sup>) and yearly average temperature<sup>11</sup>.

In terms of model (3), this becomes:

$$\Delta D_{it} = \delta + \rho \Delta D_{i,t-1} + \beta_1 \Delta Y_{it} + \beta_2 \Delta P_{it} + \beta_3 \Delta P_{jt} + \beta_4 \Delta T_{it} + \Delta u_{it} \quad ; \quad i, j = 1, \dots, N, i \neq j, t = 1, \dots, T \Delta \quad (5)$$

Computations were performed using STATA's *xtabond* procedure. We opted for robust estimators as specified in the Appendix (equations (A3) and (A5)), which are the most suitable ones under general assumptions of residual serial correlation and homoskedasticity. This choice however has the drawback of invalidating the results of the Sargan specification test: consequently we assumed the regressors to be all endogenous<sup>12</sup>. Moreover, the number of the available instrumental variables used (described in Section 5.1) was kept to a minimum, in order to be as little as possible affected by asymptotic biases.

### 3.4 Tests performed

The *xtabond* procedure automatically performs two of the validation tests defined by Arellano and Bond, i.e., the Sargan specification test and the lack of auto-correlation test. In particular, the first is based upon the assumption of lack of serial correlation (of the differenced error  $\Delta u_{it}$ ).

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<sup>10</sup> In practical terms, we considered only the cases of oil products as substitute for gas, and of gas as substitute for oil products. Note that, although demand theory often places restrictions on cross price elasticities for households, in our estimations we took a more agnostic approach and no restrictions were placed on the elasticities.

<sup>11</sup> A trend term  $\delta t$  was also inserted into the equation, but it actually does not fully capture the trend behaviour of observations, since the variables in the model are not de-trended: the specification of trend components of the variables would require, in our case, knowledge about unit roots. Thus the term only adjusts the trend slope of the fitted values of the original model.

<sup>12</sup> Formally:  $\text{CORR}(X_{is}, u_{it}) = 0$  for  $t > s$ ; with  $X_{it}$  representing each single regressor.

The second test, used to test lack of correlation of second order, provides a fundamental check for the consistency of estimators. However, for what stated before it is best recommendable to do not completely rely upon its results, and consider the estimates likely to be to a certain extent biased.

#### **4. Results**

Tables 2, 3, 4 and 5 present, respectively for households, industrial and commercial users (service sector, with two alternative specifications), the estimated values of elasticities and of the autoregressive coefficient, together with the p-values of the respective significance test. The models for households sector are mostly consistent with the underlying economic theory: with the exception of coal demand, expectations upon sign and magnitude of the estimates have been respected. In particular we observe a positive relationship between income and energy demand, and negative relationships between energy vectors' demands and own prices. By contrast, a (mildly) significant and positive relationship with the price of alternative fuels is present only in the case of gas, whose demand is positively affected by an increase in the price of oil products. Interestingly, the reverse does not happen: the correspondent elasticity for the oil products model is negative but not significant. A possible explanation is the different range of alternative household use of the two energy vectors: gas is mainly used for heating, while oil products include heating diesel as well as transportation fuels. Thus "oil products" can be a substitute for gas, (the switching costs are well within a long-term family budget), but the scope for the reverse to happen is rather limited. The negative relationship between coal for households use and RGDP may point to the nature of inferior good of coal for heating use; the value pertinent to the lagged dependent variable is admissible and consistent with the other cases. More puzzling appears the positive and significant sign of the elasticity to temperature of coal demand: it might be partially due to the low popularity of coal for heating use. Price seem not to bear a significant relationship with coal demand. The missing observation bias, which in the case of coal is stronger due to the sensibly lesser amount of observations, may have also partially caused these results. Some other statistically not-significant estimates (e.g. the elasticity to RGDP in the case of oil products demand) can be regarded, in the context of to the whole set of residential demand results, as acceptable.

Note that in all models presented, the constant, which captures the effect of the trend in the differential approach of equation (11), is not included. It was decided to drop it because in the alternative specification in which it was included, it was of negligible magnitude and, most importantly, never significant in all the residential demand models. In other word, these models are all stationary.

## TABLE 2 ABOUT HERE

The results are less reliable for industrial users demands: in this case the economic expectations are still respected, including the non significance of the elasticities to the temperature, but the significance of the remaining elasticities is rather uncertain, in particular in the case of prices. In order to investigate this issue, we fitted models of the same general form for sub-aggregated voices of demand<sup>13</sup>, because they can best take account of the phenomenon under investigation. A comparison between original and restricted fitted models is available from the authors upon request. Only for coal demand the restricted model's can be considered a better specification, in the sense of statistical significance of estimates, while the outcomes for the remaining vectors are uncertain. A secondary issue, regarding the industrial demand of oil, is to establish at what extent the disaggregated demand concerning High Sulphur Oil can provide a better result with respect to the original one based on average prices<sup>14</sup>. The alternative model has practically the same estimated parameters, but it does not yield any significant gain with respect the one based on average oil prices in terms of variability of the estimates. Again, alternative estimates are available upon request.

## TABLE 3 ABOUT HERE

## TABLE 4 ABOUT HERE

Table 4 and Table 5 illustrate the service sector case<sup>15</sup>. Here, a situation similar to the industrial case arises: the lagged dependent turns out to be most significant explanatory variable, while the relationship with the other explanatory variable is not very much supported by the data. Considering GDP per capita instead of GDP brings about only modest improvements in the estimates: the significance of the elasticity of prices and income increases. Also, temperatures display a mildly significant negative effect on demand in the case of electricity and coal. The sample size for coal is however too small to draw any robust conclusion.

## TABLE 5 ABOUT HERE

Finally, we looked at the relevance of the trend for the industrial and commercial demand models<sup>16</sup>. It turns out that in the case of industrial demand, parameter estimates are not invariant to the inclusion of the trend. In particular, both the sign and magnitude of the elasticity of industrial

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<sup>13</sup> The restricted models consider the demand of each energy vector by public and auto-producer electricity plants and public and auto-producer CHP Plants. Other variables remained the same.

<sup>14</sup> Because the price series for High Sulphur Oil has the highest number of observations.

<sup>15</sup> Here we present both the models including GDP among the explanatory variables, and the alternative ones including GDP per capita, because there was no clear a priori reason to exclude either type of models.

<sup>16</sup> Results for the model in which the trend is included are available upon request.

demand for coal and electricity to temperature are affected. However, temperature elasticity remains non significant for all the energy vectors. The trend parameter itself is however often significant, although it remains of negligible magnitude (bar the case of coal).

In the case of commercial demand, the trend is hardly ever significant (the only exception is again, coal), and its inclusion makes the only mildly meaningful temperature elasticity (the electricity demand's one) to become not significant.

Thus from our particular point of view, including a trend parameter does not help; at most, it adds evidence to the lack of relationship between industrial energy demand and temperature.

In all models, the estimates of the autoregressive parameter for the various categories of demand are high, and, with no exception, highly significant. This result is consistent with the underlying econometric theory, in the sense that demand for the various energy vectors display temporal persistence. Moreover, the regressive relationship between the dependent variable and its first lag is always highly significant. We regard this outcome as an indication of consistence of the whole set of results, and thus, as stated before, that the sources of bias previously indicated in Section 3 do not affect too heavily the results of the analysis.

Another argument in favour of the above statement derives from considering the results concerning the efficiency of the estimates. Tables 6 shows the estimated standard errors and 95% confidence intervals of the variables included in our household models (we do not include analogous tables for the industrial and commercial sectors for economy of space). The estimation procedure performed quite well. Once again, the best results pertain to the lagged dependent variable: in brief, by considering 95% confidence intervals it is easily verifiable that the results are consistent with what stated before. Aside from this, it is interesting to note that a certain amount of variability of estimates is, on the theoretical ground, imputable to the parameter homogeneity of the model, i.e., the hypothesis of identity of the regression coefficients for each unity of the panels of data.

#### TABLE 6 ABOUT HERE

For household demand we observe in most cases appreciable values of standard errors of the estimates, together with confidence intervals whose extremes have the same sign of the parameter under scrutiny. Exceptions to the latter statement are Coal and Oil Products demand; however, they always occur in concomitance with not significant estimates, and, consequently, does not point to a mis-specified result. Given the values of variation coefficients in Table 7, we can conclude that the estimates perform reasonably well in terms of efficiency: mostly, the standard errors approximately possess half the magnitude of the estimates. The same conclusion can be drawn by considering the respective 95% confidence intervals.

In the case of the industrial and commercial demand models, results are rather similar for what concerns both the magnitude of variability and the sign of 95% confidence intervals. This however is not the case for temperature in the industrial models. This is an admissible outcome, given that temperature coefficient estimates never pass their own significance test. For the remaining variables we observe once again a strict correspondence between mis-specified intervals and lack of statistical significance of estimates; moreover, the estimates display once again appreciable efficiency.

TABLE 7 ABOUT HERE

## **5. Conclusions**

This paper is a first attempt to investigate the effect of climate on the demand for different energy vectors by residential, commercial and industrial users, by means of a dynamic panel analysis of the demand for coal, gas, electricity, oil and oil products in OECD and (a few) non-OECD countries.

Previous studies on the relationship between energy demand and temperature generally focused on single country (or even single province) time series analysis.

The main rationale for using a dynamic panel approach has been to try and extrapolate a long-run relationship between temperature and energy demand, using cross-sectional variation as a spatial analogy of different long-run equilibrium demands.

The ultimate motivation for this is to arrive to a consistent evaluation of the impact of climate change on a key class of consumption goods and primary factors such as energy vectors, which can be used as inputs for climate change simulations in an Integrated Assessment Model framework.

Results differ substantially across categories of users. Temperature has a very different influence on the demand of energy as a consumption good and on the demand of energy as a primary factor. Residential demand responds negatively to temperature increases, (but this does not happens for all energy vectors), pointing at a prevalence of heating needs in determining residential demand. By contrast, industrial demand is insensitive to temperature increases. In the case of the service sector, only electricity demand displays a mildly significant negative elasticity to temperature changes. These results appear to be invariant to variations in the specification of the models such as the inclusion of a trend parameter, or different definitions of the reference price for oil, or the restriction of the analysis of industrial demand to the most energy intensive sub-sector.

This study is quite preliminary and, as such, suffers from some obvious limitations.

Data limitations had a non-negligible role in shaping our analysis: we were confined to those data series which are available for a reasonable number of countries, enough to build up a reliable panel.

In some cases this proved just impossible: price and demand data for coal are available for just an handful of countries (particularly in the service sector case). For some explanatory variables, we had to content ourselves with second-best choices. For instance, GDP and GDP per capita are just proxies for sectoral value added and disposable income. The choice of yearly average temperature as a temperature data was also a compromise. Ideally we would have used heating and cooling degree days, which express how much temperature in a country has differed from a temperature level conventionally regarded as thermally optimal, in a given year<sup>17</sup>. Reasonably long time-series for these variables are only available for the USA and an handful of other OECD countries. We did have at our disposal seasonal and monthly temperature averages, but the information provided was no better than the yearly average one: the main conclusion that could be drawn from model specification in which seasonal and monthly temperature averages were included was still that heating demand was the main driver of the negative relationship between residential demand and temperature. Thus we decided to present only the results on yearly temperature as the most parsimonious ones<sup>18</sup>.

Another limitation of our analysis is that the equations estimated are reduced forms, which reflect both demand and supply effects. The interpretation of our coefficients as elasticities of energy vectors' demand to the corresponding explanatory variable rests on the implicit assumption that, in the long run, demand is more stable than supply. Simultaneous equations estimation for a complete demand-supply equilibrium in a dynamic panel framework is a formidable task and goes beyond the scope of our paper<sup>19</sup>.

Our current research is focused on improving the analysis in at least two regards. First, we are interested in modelling non-linear temperature effects on demand. It is in fact very likely that not only the level of the temperature matters, but also the intensity of the change. Second, we are interested in the geographical implications of the relationships under scrutiny. For instance we

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<sup>17</sup> Heating Degree Days are defined as the cumulative number of degrees within the temporal unit of observation (generally month or year) by which the mean daily temperature falls below a reference value for thermal comfort, usually 18.3°C/65°F. Cooling Degree Days are defined analogously and apply to the days in which the mean temperature is above such reference value.

<sup>18</sup> There were two practical reason for focusing on single yearly temperature elasticity parameter. The first is that, in our intention, these estimates should feed in an Integrated Assessment Model calibrated on yearly data. The second is that in order to fully account for seasonal variability, we would have needed quarterly data for prices and consumption for our panel (separately for household, industrial and commercial consumption). For any given annual temperature average, in fact, energy consumption can be very different according to whether that average is the result of a steady pattern of almost constant temperatures or of wide swings from a very cold winter to a very hot summer. The fact that climate change is expected to increase seasonal variability of temperatures adds to the relevance of this issues. We have been unable so far to access data of this kind of detail for the same sample used for the analysis presented in this paper. Nevertheless, we are aware of the implications of seasonal variability for energy demand, and our ongoing research is focusing on designing a strategy to tackle this issue.

<sup>19</sup> In partial support to our approach Engsted and Bentzen (1997) broadly indicate our specification (energy demand dependent from prices income and temperature) as the “the way it has been usually done in the literature”.

intend to test the opportunity of using North /South sub-panels and the explore the issue of the extrapolation of non-OECD temperature elasticities.

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## Appendix: Arellano-Bond estimators

*General form of the estimators:*

Arellano and Bond (1991) set up the GMM method of estimation in a wide class of models and discuss three specification tests.

The construction of the matrixes of instrumental variables, which from now on will be indicated with:  $\mathbf{Z} = (\mathbf{Z}'_1, \dots, \mathbf{Z}'_i, \dots, \mathbf{Z}'_N)'$ , follows the guideline of Anderson and Hsiao (1981). In brief, considering the lagged endogenous variables:  $\Delta y_{i,t-1}$ ,  $t=2, \dots, T$ ; one can select all past levels of the original dependent (more suitable than first differences); for any  $t$  as above the available IV are:  $y_{i,t-2}, \dots, y_{i,t}$ . It is also possible to employ all the first differences of the remaining variables (for example:  $\Delta x_{it}^{(h)}$ ,  $t=2, \dots, T$ ) if they satisfy the strict exogeneity assumption. If there exists some endogenous or predetermined regressor, say  $x_{it}^{(h)}$ , one must make a selection among the set of past levels:  $\Delta x_{it-1}^{(h)}, \dots, \Delta x_{it}^{(h)}$ ,  $t=2, \dots, T$ ; which will play the role of instruments for  $\Delta x_{it}^{(h)}$ .

In any case one obtains block-diagonal matrixes  $\mathbf{Z}_i$ , which give rise to the moment restrictions:

$$E[\mathbf{Z}'_i \Delta \mathbf{u}_i] = E[\mathbf{Z}'_i (\Delta \mathbf{y}_i - \Delta \mathbf{W}'_i \boldsymbol{\gamma})] = \mathbf{0} \quad ; \quad i = 1, \dots, N \quad . \quad (\text{A1})$$

For example, in the case in which all the regressors  $x_{it}^{(h)}$  are exogenous, the generic  $\mathbf{Z}_i$  with the full set of available IV has the form:

$$\mathbf{Z}_i = \text{diag} \left( [y_{i0}, \Delta \mathbf{x}'_i], [y_{i0}, y_{i1}, \Delta \mathbf{x}'_i], \dots, [y_{i0}, \dots, y_{iT-1}, \Delta \mathbf{x}'_i] \right) \quad . \quad (\text{A2})$$

where  $\Delta \mathbf{x}_i$  is the stacked vector of:  $\Delta \mathbf{x}_{it}$ ;  $t=2, \dots, T$ .

For any choice of the instruments, the general form of GMM estimators based on restrictions (A1) is the following:

$$\begin{aligned} \hat{\boldsymbol{\gamma}}_{\text{GMM}} &= (\Delta \mathbf{W}' \mathbf{Z} \mathbf{A}_N \mathbf{Z}' \Delta \mathbf{W})^{-1} \Delta \mathbf{W}' \mathbf{Z} \mathbf{A}_N \mathbf{Z}' \Delta \mathbf{y} = \\ &= \left[ \left( \sum_{i=1}^N \Delta \mathbf{W}'_i \mathbf{Z}_i \right) \mathbf{A}_N \left( \sum_{i=1}^N \mathbf{Z}'_i \Delta \mathbf{W}_i \right) \right]^{-1} \left( \sum_{i=1}^N \Delta \mathbf{W}'_i \mathbf{Z}_i \right) \mathbf{A}_N \left( \sum_{i=1}^N \mathbf{Z}'_i \Delta \mathbf{y}_i \right) ; \end{aligned} \quad (\text{A3})$$

where  $\mathbf{A}_N$  is an arbitrary  $N \times N$  matrix of weights,  $\Delta \mathbf{W} = (\Delta \mathbf{W}'_1, \dots, \Delta \mathbf{W}'_N)'$ ,  $\Delta \mathbf{y} = (\Delta \mathbf{y}'_1, \dots, \Delta \mathbf{y}'_N)'$ , and  $\mathbf{Z}$  defined as above. Thus we obtain:

- one-step estimator with  $\mathbf{A}_N = \left( \sum_{i=1}^N \mathbf{Z}'_i \mathbf{Z}_i \right)^{-1}$  ; (A4)

- two-step estimators with  $\mathbf{A}_N = \left( \sum_{i=1}^N \mathbf{Z}'_i \tilde{\boldsymbol{\Omega}}_i \mathbf{Z}_i \right)^{-1}$ , or  $\mathbf{A}_N = \left( \sum_{i=1}^N \mathbf{Z}'_i \Delta \tilde{\mathbf{u}}_i \Delta \tilde{\mathbf{u}}'_i \mathbf{Z}_i \right)^{-1}$  (A5);

where  $\tilde{\Omega} = \sum_{i=1}^N \Delta\tilde{\mathbf{u}}_i \Delta\tilde{\mathbf{u}}_i'$  is a matrix of arbitrary consistent estimates of the unrestricted variances and covariances of the errors of model (3)<sup>20</sup>.

*Asymptotic behaviour:*

A relevant issue for the present discussion is that the Arellano-Bond estimators perform optimally in the fixed  $T$ , large  $N$  context; however their performance worsens for large  $T$ , for any value of  $N$ . In the case of  $T$  fixed, large  $N$  it is recommended to use the full set of instrumental variables discussed above, and adopt the one-step estimator under homoskedasticity and lack of serial correlation of the errors, or else the two-step estimators (7) and (8). Arellano (2003b) found, under restrictive assumptions, that with large  $N$ , large  $T$  the one-step estimator is asymptotically biased of order  $O(m*N^{-1})$ , with  $m=k-1$ , i.e., the number of regressors other than  $\Delta y_{i,t-1}$ .

However, the loss of performance can be explained by the fact<sup>21</sup> that the Arellano-Bond estimators implicitly involve particular forms of (cross-section specific, unrestricted) linear projection of the  $\Delta\mathbf{w}_{it}$ 's onto the columns of  $\mathbf{Z}_i$ ; for example, if the  $x_{it}^{(j)}$ 's are all predetermined we can write:

$$\mathbf{p}_{it} = \boldsymbol{\pi}'_{t1} \mathbf{z}_{it} + \boldsymbol{\pi}'_{t2} \mathbf{z}_{i,t-1} + \dots + \boldsymbol{\pi}'_{tt} \mathbf{z}_{it} \quad ; \quad i = 1, \dots, N, \quad t = 2, \dots, T \quad (\text{A6})$$

In any case the projections comprise a  $T$ -dependent, monotonically increasing number of addends, giving rise to the problems of “consistently estimating” the respective coefficients:  $\boldsymbol{\pi}_{ts}$  for large  $T$ . In particular, it may cause asymptotical bias of the estimates for large  $N$ , large  $T$ , if the ratio  $T/N$  tends to a non negligible constant.

In order to bypass this problem one can consider two strategies:

*1) Adopt an alternative estimator.*

Considering the class of the IV-based ones, Arellano (2003a) suggests a Two-Stage Least Squares estimator in the case of exogenous regressors, which involves linear projections with a fixed number of addends, or else a “stacked-IV” estimator, which uses the first  $J$  lags:  $\mathbf{z}_{it}, \dots, \mathbf{z}_{i,t-J+1}$ ,  $J$  fixed, to form common instruments for all periods.

*2) Impose restrictions on the linear projections.*

One technique that presents such feature is developed in Arellano (2003b), but it requires much more complicated computations. However, intuitively this complexity is due to the objective of obtaining an estimator with good performances in each asymptotic context, and this implies both keeping constant the number of coefficients of the (restricted) linear projections, and exploiting the information of all available periods.

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<sup>20</sup> The term  $\Delta\tilde{\mathbf{u}}_i$  stands for the estimated residuals of the same model.

<sup>21</sup> For details see Arellano (2003a), paragraphs 7.3.2, 7.3.3 and 8.7.

## TABLES

Energy Vector	Sector		
	Households	Industrial	Services
Coal	7 (147)	8 (168)	3 (63)
Electricity	25 (525)	22 (462)	24 (504)
Natural Gas	19 (399)	11 (231)	15 (314)
Oil	-	26 (546)	-
Oil Products	16 (336)	29 (609)	14 (294)

*Table 1: Number of cross sections and total observations for category of demand.*

ENERGY VECTORS	VARIABLES				
	Lagged Dependent	RGDP per capita	End-user Own Price	Price Alternative Fuel	Temperature
Coal	0.9357 (0.000)	-0.7599 (0.025)	0.1650 (0.022)		2.845 (0.000)
Electricity	0.8983 (0.000)	0.0977 (0.075)	-0.0183 (0.004)		-0.5762 (0.000)
Natural Gas	0.8205 (0.000)	0.3169 (0.000)	-0.3208 (0.004)	0.1157 (0.037)	-1.8225 (0.000)
Oil Products	0.8194 (0.000)	0.1007 (0.532)	-0.0479 (0.653)	-0.1201 (0.219)	-3.0548 (0.023)

*Table 2: Coefficient estimates and correspondent p-values for households sector models.*

ENERGY VECTORS	VARIABLES				
	Lagged Dependent	RGDP	End-user Price	Price alternative fuels	Temperature
Coal	0.1254 (0.001)	0.5458 (0.300)	-0.2028 (0.000)		-0.3851 (0.728)
Natural Gas	0.6101 (0.003)	0.2807 (0.100)	-.2185 (0.005)	.0757 (0.516)	0.0527 (0.891)
Electricity	0.7127 (0.000)	0.2543 (0.000)	-0.0239 (0.000)		0.0606 (0.624)
Oil	0.7675 (0.000)	0.2150 (0.000)	-0.0167 (0.231)		-0.629 (0.168)
Oil Products	0.7617 (0.000)	-0.0904 (0.404)	-0.2082 (0.005)	-0.1062 (0.849)	-0.3421 (0.527)

*Table 3: Coefficient estimates and correspondent p-values for industrial sector models.*

ENERGY VECTORS	VARIABLES				
	Lagged Dependent	RGDP	End-user Price	Price alternative fuels	Temperature
<b>Coal</b>	0.7589 (0.000)	-1.0514 (0.055)	0.3212 (0.170)		-2.5484 (0.064)
<b>Electricity</b>	0.9353 (0.000)	0.1031 (0.144)	-0.00954 (0.222)		-0.1984 (0.352)
<b>Natural Gas</b>	0.8057 (0.000)	0.5563 (0.023)	-0.1915 (0.434)	-0.1478 (0.910)	-0.1534 (0.440)
<b>Oil Products</b>	0.5195 (0.000)	-0.2344 (0.354)	0.3005 (0.111)	-.05852 (0.796)	-2.1340 (0.232)

*Table 4: Coefficient estimates and correspondent p-values for service sector models.*

ENERGY VECTORS	VARIABLES				
	Lagged Dependent	RGDP per capita	End-user Price	Price alternative fuel	Temperature
<b>Coal</b>	0.7851 (0.000)	-1.0631 (0.015)	0.2739 (0.166)	-	-2.7282 (0.026)
<b>Electricity</b>	0.9286 (0.000)	0.1497 (0.051)	-0.0155 (0.012)	-	-0.0332 (0.084)
<b>Natural Gas</b>	0.7861 (0.000)	0.8812 (0.024)	-0.3147 (0.144)	0.0902 (0.462)	-2.0688 (0.280)
<b>Oil Products</b>	0.4919 (0.000)	-0.4849 (0.160)	0.4690 (0.057)	-0.3535 (0.239)	-1.940 (0.198)

*Table 5: Coefficient estimates and correspondent p-values for service sector models (GDP per capita) sector.*

ENERGY VECTORS	VARIABLES				
	Lagged Dependent	RGDP pro capita	End-user Price	Price alternative fuel	Temperature
Coal	0.06217 (0.81, 1.05)	0.3392 (-1.42, -0.95)	0.00722 (0.02, 0.3)		0.4353 (1.99, 3.69)
Electricity	0.0297 (0.84, 0.96)	0.055 (-0.01, 0.20)	0.0064 (-0.03, -0.006)		0.113 (-0.79, -0.35)
Natural Gas	0.0803 (0.66, 0.98)	0.0870 (0.15, 0.49)	0.1113 (-0.54, -0.1)	0.0553 (0.007, 0.22)	0.371 (-2.45, -1.1)
Oil Products	0.0589 (0.70, 0.93)	0.1061 (-0.21, 0.42)	0.106 (-0.16, 0.25)	0.0976 (-0.31, 0.07)	1.345 (-5.69, -0.42)

*Table 6: Standard error and 95% confidence intervals of estimates for households sector models.*

ENERGY VECTORS	VARIABLES				
	Lagged Dependent	RGDP	End-user Price	Price alternative fuel	Temperature
Coal	0.07	-0.45	0.04		0.15
Electricity	0.03	0.06	-0.35		-0.20
Natural Gas	0.10	0.27	-0.35	0.48	-0.20
Oil Products	0.07	1.05	-2.21	-0.81	-0.44

*Table 7: Variation coefficients of estimates for households sector models.*

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