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Authors' addresses:

Ronald Bernstein, Reinhard Madlener
Institute for Future Energy Consumer Needs and Behavior (FCN)
School of Business and Economics / E.ON Energy Research Center
RWTH Aachen University
Mathieustrasse 6
52074 Aachen, Germany
E-mail: RBernstein@eonerc.rwth-aachen.de, RMadlener@eonerc.rwth-aachen.de

Publisher: Prof. Dr. Reinhard Madlener
Chair of Energy Economics and Management
Director, Institute for Future Energy Consumer Needs and Behavior (FCN)
E.ON Energy Research Center (E.ON ERC)
RWTH Aachen University
Mathieustrasse 6, 52074 Aachen, Germany
Phone: +49 (0) 241-80 49820
Fax: +49 (0) 241-80 49829
Web: www.eonerc.rwth-aachen.de/fcn
E-mail: post_fcn@eonerc.rwth-aachen.de

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Ronald Bernstein* and Reinhard Madlener

Institute for Future Energy Consumer Needs and Behavior (FCN), School of Business and Economics / E.ON Energy Research Center, RWTH Aachen University, Mathieustrasse 6, 52074 Aachen, Germany

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Abstract

In this paper we analyze residential natural gas demand in twelve OECD countries using time series data from 1980 to 2008. We estimate long-run demand elasticities with regard to real disposable income and real residential price of natural gas using the autoregressive distributed lag (ARDL) bounds testing procedure (Pesaran and Shin, 1999). The robustness of the long-run estimates is checked by additionally considering the FMOLS and DOLS estimators. By employing an error correction framework we also obtain estimates for the speeds of adjustment to long-run equilibrium and short-run elasticities for the individual countries. The effect of weather conditions on natural gas demand in a given year is accounted for by including heating degree days as a control variable. On average, the long-run elasticities are 0.94 with regard to income, –0.51 with regard to price and 1.35 with regard to weather. The short-run dynamics assessed by estimation of the error correction models indicate an average adjustment coefficient of –0.58, a short-run income elasticity of 0.45, a short-run price elasticity of –0.24, and a short-run weather elasticity of 0.72. Hence, on average, the short-run elasticities are approximately half in magnitude compared to their long-run counterparts.

JEL classification: Q41; Q43

Keywords: Natural gas demand; Elasticities; ARDL; Bounds testing; OECD countries; Residential

* Tel.: +49 241 80 49 832; fax: +49 241 80 49 829; e-mail: RBernstein@eonerc.rwth-aachen.de (R. Bernstein); RMadlener@eonerc.rwth-aachen.de (R. Madlener)

1. Introduction

In this paper we aim at estimating long- and short-run residential natural gas demand elasticities with regard to real disposable income and the real gas price. Our analysis is based on time series data for the period 1980 to 2008 for 12 OECD countries:[1] Austria (AT), Finland (FI), France (FR), Germany (DE), Ireland (IE), Japan (JP), Luxembourg (LU), the Netherlands (NL), Spain (ES), Switzerland (CH), the UK and the US. We take account of the spurious regression problem associated with the common existence of stochastic trends in economic time series by applying the autoregressive distributed lag (ARDL) bounds testing procedure introduced in Pesaran and Shin (1999) and Pesaran *et al.* (2001). In contrast to other approaches to cointegration, this method has the advantage of rendering pre-stage unit root tests unnecessary, which are known to have very low power.

Compared to other fossil fuels (i.e. coal and oil), natural gas currently has the smallest share in global primary energy demand. Nevertheless, its future relevance in the fuel mix is expected to increase. This is mainly due to the desirable environmental attributes of gas when compared to coal or oil. Moreover, in recent years, an increased transport and processing capacity for liquefied natural gas (LNG) and a surge in unconventional gas extraction in the US have led to a surplus in the global gas supply capacity. This trend is in favor of a development away from the traditional oil price indexation toward an independent price formation in the market for gas.

Table 1 gives an overview of projections of future (2020 and 2035) world primary energy demand by fuel. These projections are dependent on three different scenarios developed in the IEA's World Energy Outlook 2010 (WEO 2010): the *'Current Policies Scenario'*, the *'New Policies Scenario'* and the *'450 Scenario'*.[2] World demand for natural gas has increased by approximately 110% since 1980. This tendency of an increasing role of natural gas when compared to other fossil energy carriers continues in all three scenarios. In the *'New Policies*

[1] The choice of the OECD countries considered was guided by data availability.

[2] The differences between them lie in the assumptions with regard to future governmental energy policies and their success in meeting the initial policy objectives aimed at security of energy supply and climate change. While the *'Current Policies Scenario'* only considers policies which have already been adopted, the *'New Policies Scenario'* makes cautious assumptions about further future policies which would be needed to fulfill individual national commitments with regard to the abatement of greenhouse gas emissions. Finally, the *'450 Scenario'* describes a development which is consistent with the target of restricting the global temperature increase of the atmosphere to 2° C.

Scenario' and the *'450 Scenario'* the growth in gas demand exceeds both that of oil and coal, while in the *'Current Policies Scenario'* only coal demand experiences a slightly higher growth.

Table 1
World primary energy demand by fuel and scenario (demand for natural gas highlighted)

Fuel types			**Current Policies Scenario**		**New Policies Scenario**		**450 Scenario**	
	1980	2008	2020	2035	2020	2035	2020	2035
Coal	1 792	3 315 84.99%	4 307 29.92%	5 281 59.31%	3 966 19.64%	3 934 18.57%	3 743 12.91%	2 496 –24.71%
Oil	3 107	4 059 30.64%	4 443 9.46%	5 026 23.82%	4 346 7.07%	4 662 14.86%	4 175 2.86%	3 816 –5.99%
Gas	1 234	2 596 110.37%	3 166 21.96%	4 039 55.59%	3 132 20.65%	3 748 44.38%	2 960 14.02%	2 985 14.98%
Nuclear	186	712 282.80%	915 28.51%	1 081 51.83%	968 35.96%	1 273 78.79%	1 003 40.87%	1 676 135.39%
Hydro	148	276 86.49%	364 31.88%	439 59. 06%	376 36.23%	476 72.46%	383 38.77%	519 88.04%
Biomass & waste*	749	1 225 63.55%	1 461 19.27%	1 715 40.00%	1 501 22.53%	1 957 59.76%	1 539 25.63%	2 316 89.06%
Other renewables	12	89 641.67%	239 168.54%	468 425.84%	268 201.12%	699 685.39%	325 265.17%	1 112 1 149.44%
Total	7 229	12 271 69.75%	14 896 21.39%	18 048 47.08%	14 556 18.62%	16 748 36.48%	14 127 15.13%	14 920 21.59%

Notes: * Includes traditional and modern use. Absolute figures are in Mtoe. Source: IEA (2011), own illustration. Percentages in the second column represent the change in demand from 1980 to 2008. Percentages in all other columns represent the selected change in demand from 2008 to 2020 and 2035, respectively.

Table 2 presents a few descriptive statistics on natural gas consumption in 2008 for the countries considered in the following analysis. A glance at the statistics reveals a considerable extent of heterogeneity in consumption patterns across countries. First of all, total final gas consumption per capita (TFC_{GPC}) is 0.63 tons of oil equivalent (toe) on average and varies substantially between 0.16 toe in Finland and 1.40 toe in Luxembourg. Second, the share of gas consumption in total final energy consumption (TFC_{SG}) is 19.97% on average and ranges from a minimum of 3.39% in Finland to a maximum of 42.18% in the Netherlands. Third, the share of residential consumption in TFC_G (TFC_{GSR}) is 35.92% on average and varies between a minimum of 4.55% in Finland and a maximum of 60.42% in the UK.

There are many studies on the econometric analysis of (residential) natural gas demand, but nearly all of these are from the 1960s to the 1980s. More recent studies, especially from the 2000s, are very rare, and none known to us take the problems related to non-stationarity in the data (especially the possibility of 'spurious' regressions) into account. Table 3 provides an overview of recent studies: Asche *et al.* (2008) analyze residential natural gas demand in 12 EU member countries, using panel data for the time period 1978 to 2002. Their shrinkage estimator reveals an income elasticity of 3.32 in the long run and 0.81 in the short run. For the price elasticity the estimates are –0.10 and –0.03 for the long run and the short run, respectively.

Table 2

Descriptive statistics for natural gas consumption of selected OECD countries in 2008

Country	**TFC_G**	**TFC_{GPC}**	**TFC_{SG}**	**TFC_{GSR}**
Austria	4 462 000	0.535	17.71%	26.33%
Finland	836 000	0.157	3.39%	4.55%
France	31 436 000	0.490	20.71%	44.53%
Germany	56 860 000	0.692	26.89%	51.03%
Ireland	1 655 000	0.373	13.53%	40.30%
Japan	32 258 000	0.252	11.44%	28.11%
Luxembourg	683 000	1.398	17.58%	39.68%
Netherlands	19 577 000	1.191	42.18%	36.29%
Spain	14 813 000	0.325	16.22%	24.57%
Switzerland	2 570 000	0.333	12.59%	39.53%
UK	46 518 000	0.758	34.77%	60.42%
US	317 766 000	1.053	22.65%	35.70%
MIN	683 000	0.157	3.39%	4.55%
MEAN	**44 119 500**	**0.630**	**19.97%**	**35.92%**
MAX	317 766 000	1.398	42.18%	60.42%

Notes: TFC_G: total final consumption of gas; TFC_{GPC}: total final consumption of gas per capita; TFC_{SG}: share of gas in total final energy consumption; TFC_{GSR}: share of residential gas consumption in TFC_G. All values refer to gas consumption for energy use only. Absolute figures (TFC_G and TFC_{GPC}) in toe. Source: IEA, statistics by country, energy balances; own illustration.

Berkhout *et al.* (2004) use fixed effects to estimate residential natural gas demand elasticities in the Netherlands. The estimates are –0.27 (a counterintuitive value) for the long-run income and –0.19 (not significant) for the long-run price elasticity, respectively. Using the shrinkage estimator, Joutz *et al.* (2008) estimate elasticities for the US based on panel data. Their price elasticity estimates are –0.18 in the long run and –0.09 in the short run. Using an error-components and seemingly unrelated regression (SUR) approach, Lin *et al.* (1987) estimate elasticities for the US based on panel data from 1960 to 1983. Their estimates for the income elasticities are 0.57 in the long run and 0.11 in the short run, respectively. For the price elasticity, their estimates are –1.22 for the long run and –0.15 for the short run.

Table 3
Residential natural gas demand studies

Study	Country	Method	Data	Elasticity estimates	
				Income	Price
Asche *et al.* (2008)	12 EU countries	Shrinkage estimator*	Panel data (annual), 1978–2002	*L*: 3.32 *S*: 0.81	*L*: –0.10 *S*: –0.03
Berkhout *et al.* (2004)	Netherlands	Fixed effects	Panel data (annual), 1992–1999	*L*: –0.27	*L*: *–0.19*
Joutz *et al.* (2008)	US	Shrinkage estimator	Panel data (monthly), 1980–unclear	–	*L*: –0.18 *S*: –0.09
Lin *et al.* (1987)	US	Error-components & SUR	Panel data (annual), 1960–1983	*L*: 0.57 *S*: 0.11	*L*: –1.22 *S*: –0.15

Notes: S and *L* denote estimates for the short and the long run, respectively. * Asche *et al.* (2008) also use fixed effects, random effects and OLS estimators, but the results appear to be rather implausible. Estimates printed in *italics* are not significantly different from zero.

After this introduction on the aim, scope and original contribution of our study and an overview of the related literature our paper proceeds as follows. In Section 2, we provide the analytical framework for the econometric analysis undertaken. Section 3 gives a methodological overview of the applied estimation and testing procedures applied, while Section 4 discusses the data, the application of the model and the results obtained from the analysis. Section 5 concludes.

2. Analytical framework

Similarly to the residential electricity demand function from the last section, natural gas demand can generally be expressed as a function of several determinants:

$$G_t = f\left(Y_t, P_t, X_t\right), \tag{1}$$

where G_t is residential natural gas consumption per capita, Y_t is real net disposable income, P_t is the real residential natural gas price and X_t stands for further control variables, all at time *t*. As most of the natural gas in the residential sector is used for heating purposes[3], a variable which controls for the temperature is included as well (heating degree days, HDD). More specifically, for the long-run natural gas demand relationship in the residential sector we chose the following (constant elasticity) functional form:

$$G_t = \beta_0 \exp(\beta_1 t) Y_t^{\beta_2} P_t^{\beta_3} HDD_t^{\beta_4}, \tag{2}$$

where HDD_t are heating degree days and the βs are the coefficients to be estimated. Note that initially, following other studies, we also considered the price of electricity as a substitute for natural gas. But as the estimates of the respective cross-price elasticities were not significant, we omitted these in order to gain degrees of freedom.

3. Methodology

A well-known drawback of testing for nonstationarity in the data-generating process of time series is the very low power of unit root tests. With regard to this problem, a method which has received considerable attention over the past years is the autoregressive distributed lag (ARDL) bounds testing approach to cointegration developed by Pesaran and Shin (1999) and Pesaran *et al.* (2001). A major advantage of this approach is that information regarding the order of integration of the individual variables is not needed for testing on the existence of a long-run relationship between them.[4] Hence, the pretesting for unit roots, which is required in other cointegration approaches, can be omitted. Instead, the significance of a long-run relationship is tested using critical value bounds, which are determined by the two extreme cases that all variables are $I(0)$ (the lower bound) and that all variables are $I(1)$ (the upper bound).

Taking natural logarithms of Eq. (2) and adding an error term yields the most general econometric specification of the long-run residential natural gas demand function used:

[3] A minor share of natural gas consumption is attributable to cooking.
[4] More precisely, it is not relevant whether the variables are $I(0)$ or $I(1)$. For $I(2)$ variables this approach is not valid. But this case rarely occurs with the kind of data at hand.

$$g_t = \beta_0 + \beta_1 t + \beta_2 y_t + \beta_3 p_t + \beta_4 hdd_t + \varepsilon_t , \quad (3)$$

where g_t = ln(G_t); y_t = ln(Y_t); p_t = ln(P_t); and hdd_t = ln(HDD_t). The βs are the long-run coefficients and ε_t is a white noise error term.

The first step of the bounds testing approach is to estimate the following unrestricted error correction model using OLS:

$$\begin{aligned} \Delta g_t = c + dt + \phi_1 g_{t-1} + \phi_2 y_{t-1} + \phi_3 p_{t-1} + \phi_4 hdd_{t-1} \\ + \sum_{i=1}^{k} \varphi_{1,i} \Delta g_{t-i} + \sum_{i=1}^{l} \varphi_{2,i} \Delta y_{t-i} + \sum_{i=1}^{m} \varphi_{3,i} \Delta p_{t-i} + \sum_{i=1}^{n} \varphi_{4,i} \Delta hdd_{t-i} + u_t , \end{aligned} \quad (4)$$

where the ϕ are the long-run multipliers, c is a drift term, φ are the short-run coefficients and u_t is a white noise error term. Due to the fact that it is not clear *a priori* whether y, p and hdd are the long-run forcing variables for natural gas consumption, current values of Δy, Δp and Δhdd are excluded from Eq. (4).

As a second step, an F-test on the joint hypothesis that the long-run multipliers of the lagged level variables are all equal to zero, against the alternative hypothesis that at least one long-run multiplier is non-zero, is conducted, i.e.:

H_0: $\phi_1 = \phi_2 = \phi_3 = \phi_4 = 0$;

H_1: $\phi_1 \neq 0$, or $\phi_2 \neq 0$, or $\phi_3 \neq 0$, or $\phi_4 \neq 0$.

Critical values are provided by Pesaran and Pesaran (2009, p.544). These depend on the number of regressors and the deterministic terms included. For each of the conventional significance levels, two sets of critical values are given, which constitute the lower and the upper bound. The lower bound represents the critical values for the case in which all included variables are assumed to be $I(0)$, while the upper bound assumes all the variables to be $I(1)$. Hence, all possible combinations of orders of integration for the single variables are covered. If the calculated F-statistic lies above the upper bound, the null hypothesis of no cointegration can be rejected, irrespective of the number of unit roots in the single variables. On the other hand, if it is below the lower bound, the null hypothesis is not rejected. Only if the F-statistic lies between the bounds, the result of the inference is inconclusive, given that the order of integration of the single variables is unknown.

If the existence of a significant cointegration relationship is identified by the bounds F-test, the next step is to select the optimal ARDL specification of Eq. (4). This process is guided by the Akaike Information Criterion (AIC) and the Schwarz Bayesian Criterion (SBC). Furthermore, the properties of the residuals are checked to ensure the absence of serial correlation.

A representation of the ARDL(k,l,m,n) model in the general case is

$$g_t = \alpha_c + \alpha_d t + \sum_{i=1}^{k} \alpha_{1,i} g_{t-i} + \sum_{i=0}^{l} \alpha_{2,i} y_{t-i} + \sum_{i=0}^{m} \alpha_{3,i} p_{t-i} + \sum_{i=0}^{n} \alpha_{4,i} hdd_{t-i} + w_t \,, \tag{5}$$

where w_t is an error term and k, l, m, and n are the lag lengths of the single variables.

The long-run coefficients are constructed as non-linear functions of the parameter estimates of Eq. (4):

$$\beta_0 = \frac{\alpha_c}{\left(1 - \sum_{i=1}^{k} \alpha_{1,i}\right)}, \tag{6}$$

$$\beta_1 = \frac{\alpha_d}{\left(1 - \sum_{i=1}^{k} \alpha_{1,i}\right)} \quad \text{and} \tag{7}$$

$$\beta_j = \frac{\sum_{i=0}^{q} \alpha_{j,i}}{\left(1 - \sum_{i=1}^{k} \alpha_{1,i}\right)} \tag{8}$$

with $j = \{2, 3, 4\}$ and $q = \{k, l, m, n\}$. β_0 and β_1 are the constant and the deterministic trend in the long-run model, Eq. (3), whereas the β_j are the long-run slope coefficients.

Finally, the (dynamic) short-run coefficients for the error correction representation are estimated according to

$$\Delta g_t = \theta_c + \theta_d \Delta t + \theta_{ect} ECT_{t-1} + \sum_{i=1}^{k} \theta_{1,i} \Delta g_{t-i} + \sum_{i=1}^{l} \theta_{2,i} \Delta y_{t-i} + \sum_{i=1}^{m} \theta_{3,i} \Delta p_{t-i} + \sum_{i=1}^{n} \theta_{4,i} \Delta hdd_{t-i} + v_t \,, \tag{9}$$

where $ECT_{t\text{-}1}$ is the error correction term resulting from the estimated long-run equilibrium relationship, Eq. (3), and θ_{ect} is the coefficient reflecting the speed of adjustment to long-run equilibrium, i.e. the percental annual correction of a deviation from the long-run equilibrium the year before.

4. Empirical analysis

4.1. Data

For the following analysis we gathered data on residential natural gas consumption, net disposable income, residential natural gas price, CPI and heating degree days for as many OECD countries as possible. Residential natural gas consumption and nominal natural gas prices for the time period 1978 to 2008 were obtained from the IEA database 'Energy Balances of OECD Countries' and 'Energy Prices & Taxes', respectively, while net disposable income and total population are from the OECD database (http://stats.oecd.org). The nominal price and income data are deflated using the CPI, also provided by the OECD, while natural gas consumption and real disposable income are divided by total population in order to attain per capita values. Finally, the heating degree day indexes are taken from Eurostat (http://epp.eurostat.ec.europa.eu).[5] Data (non-)availability leaves us with the following countries: Austria, Finland, France, Germany, Ireland, Japan, Luxembourg, the Netherlands, Spain, Switzerland, the UK and the US. For Japan and the US, unfortunately, heating degree days are not provided by Eurostat.

Figures 1–4 display the time series of residential natural gas consumption (measured in tons of oil equivalent, toe), real disposable income (measured in constant 1000 €, base year 2000 = 100), real residential natural gas price (measured in constant 1000 € / toe, base year 2000 = 100) and heating degree days, respectively.

Visual inspection of the single time series reveals the following trends:

- Most countries reveal an overall upward trend in residential natural gas consumption. Exceptions are the Netherlands and the US. Most of the gas consumption series have a local peak in the year 1996, which coincides with a peak in the heating degree days due to a harsh winter at that time.

[5] The heating degree days index is calculated as follows: HDD = (18 °C – T_M) x D if T_M is lower than or equal to a heating threshold of 15 °C and is zero if T_M is greater than this threshold, where $T_M = (T_{MIN} + T_{MAX})/2$ is the mean outdoor temperature over a period of D days.

- All countries reveal an overall upward trend in real disposable income. In nearly all the series, the dampening effect on the economy of the financial crisis in 2008 can be seen.

- Coinciding with the second oil price shock, real natural gas prices reach their highest levels at the beginning of the 1980s and, then, fall to relatively low levels during the late 1980s. Only since the year 2000 an overall upward trend for most of the series can be identified.

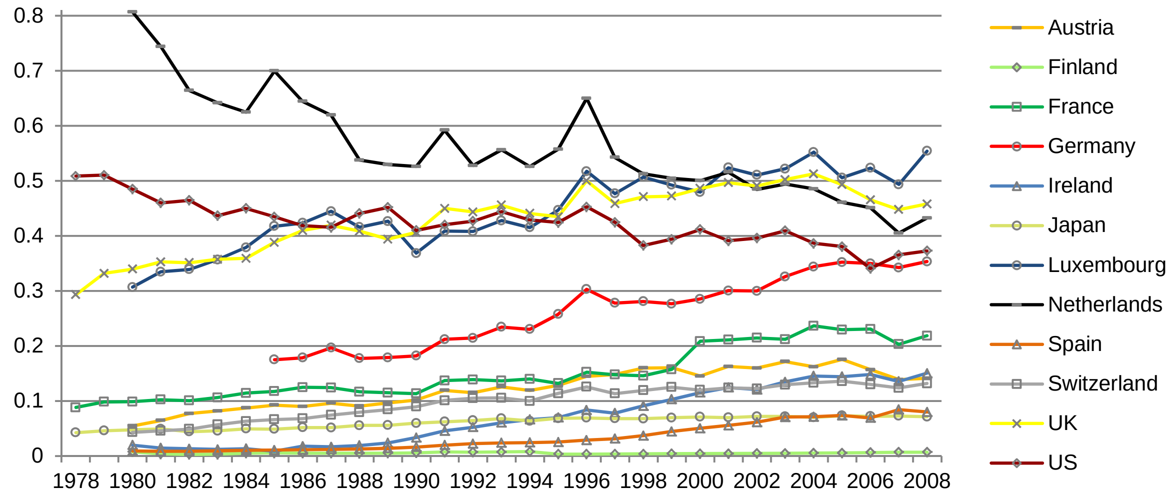

Fig. 1: Residential natural gas consumption per capita (in ktoe).
Source: IEA statistical database, own illustration.

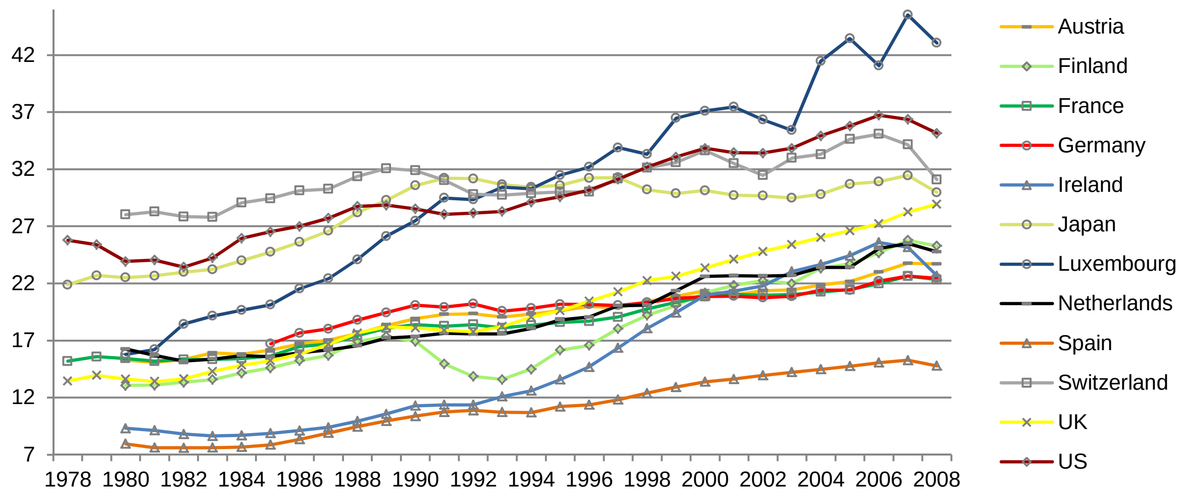

Fig. 2: Real net disposable income per capita (in 1000 €), 2000 = 100.
Source: OECD statistical database, own illustration.

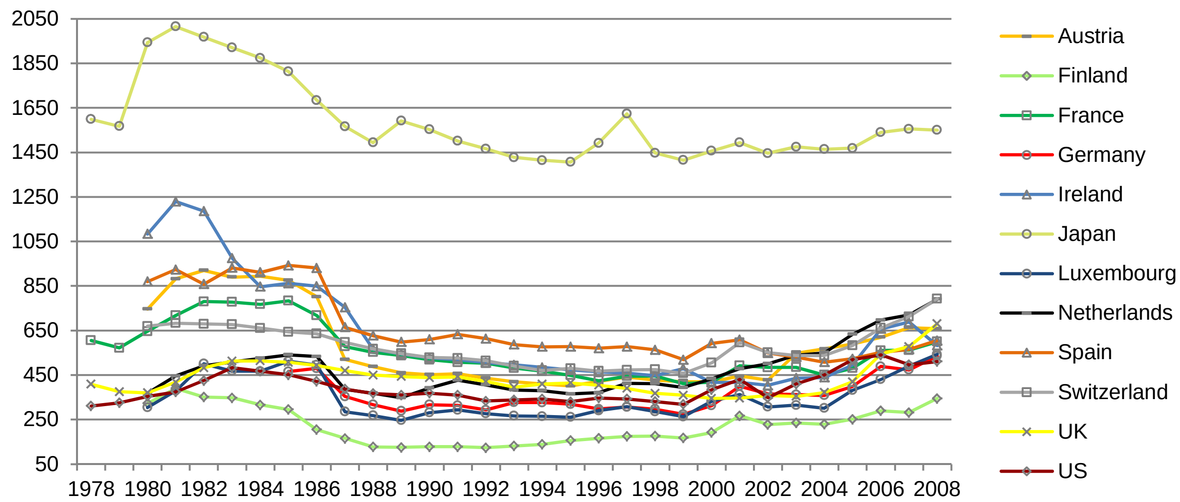

Fig. 3: Real residential natural gas prices (in 1000 €/toe), 2000 = 100.
Source: IEA statistical database, own illustration.

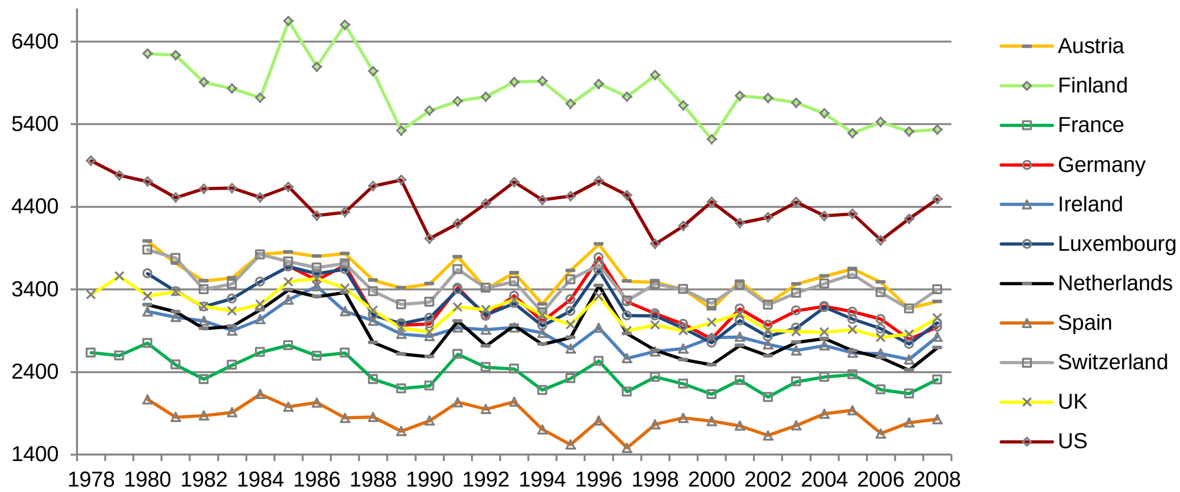

Fig. 4: Heating degree days.
Source: Eurostat statistical database, own illustration.

4.2. Bounds tests for cointegration

As a first step of the ARDL / bounds testing procedure we estimate Eq. (4) for each country using OLS. As our analysis is based on annual data, we consider lag lengths of one and two. A deterministic trend is included whenever significant. Next, we conduct an *F*-test on the joint significance of the lagged variables in levels. The results of the *F*-tests for all countries are given in Table 4, while the relevant critical value bounds are given in Table 5.[6] Only for

[6] In order to rule out the possibility of dealing with *I*(2) variables, which would invalidate the inference on the basis of these critical value bounds, we conduct the ERS (Elliott-Rothenberg-Stock, see Elliott *et al.*, 1996) unit root test on the variables in first differences. The results are summarized in Table A.1 in the appendix. For all the

France and Spain the F-statistic indicates no joint significance. For all other countries the null hypothesis of no long-run relationship is rejected at least at the 10% level.

Table 4
Bounds F-tests for a cointegration relationship

Country	Lag length: 1			Lag length: 2		
Austria	$F_g(g \mid y, p, hdd) =$	3.749**	[0.022]	$F_g(g \mid y, p, hdd) =$	5.013**	[0.011]
Finland	$F_g(g \mid y, p, hdd) =$	4.779***	[0.008]	$F_g(g \mid y, p, hdd) =$	5.231***	[0.010]
France	$F_g(g \mid y, p, hdd) =$	1.743	[0.182]	$F_g(g \mid y, p, hdd) =$	1.882	[0.170]
Germany^T	$F_g(g \mid y, p, hdd) =$	2.915*	[0.067]	$F_g(g \mid y, p, hdd) =$	4.387**	[0.043]
Ireland	$F_g(g \mid y, p, hdd) =$	3.935**	[0.019]	$F_g(g \mid y, p, hdd) =$	7.236***	[0.003]
Japan^T	$F_g(g \mid y, p) =$	13.869***	[0.000]	$F_g(g \mid y, p) =$	3.188**	[0.050]
Luxembourg	$F_g(g \mid y, p, hdd) =$	4.134**	[0.016]	$F_g(g \mid y, p, hdd) =$	3.777**	[0.033]
Netherlands^T	$F_g(g \mid y, p, hdd) =$	3.581**	[0.027]	$F_g(g \mid y, p, hdd) =$	4.060**	[0.026]
Spain	$F_g(g \mid y, p, hdd) =$	1.160	[0.363]	$F_g(g \mid y, p, hdd) =$	1.623	[0.232]
Switzerland^T	$F_g(g \mid y, p, hdd) =$	6.114***	[0.003]	$F_g(g \mid y, p, hdd) =$	4.198**	[0.024]
UK	$F_g(g \mid y, p, hdd) =$	2.601*	[0.067]	$F_g(g \mid y, p, hdd) =$	2.832	[0.062]
US^T	$F_g(g \mid y, p, hdd) =$	3.926***	[0.017]	$F_g(g \mid y, p) =$	4.702***	[0.013]

Notes: ^{T} indicates the inclusion of a deterministic trend. p-values are reported in brackets. ***, ** and * denote significance at the 1%, 5% and 10% level, respectively.

Table 5
Critical value bounds

k	**90% level**		**95% level**		**99% level**	
	$I(0)$ Lower Bound	$I(1)$ Upper Bound	$I(0)$ Lower Bound	$I(1)$ Upper Bound	$I(0)$ Lower Bound	$I(1)$ Upper Bound
Panel A: Critical values for models with intercept						
3	2.711	3.800	3.219	4.378	4.385	5.615
Panel B: Critical values for models with intercept and trend						
2	4.205	5.109	4.903	5.872	6.520	7.584
3	3.484	4.458	4.066	5.119	5.315	6.414

Notes: k denotes the number of regressors. Critical values are taken from Table B.1 in Pesaran and Pesaran (2009, p.544).

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series the null hypothesis of a unit root is rejected at the 10% level. Hence, the test results suggest that none of the variables is integrated of order two, $I(2)$.

4.3. Long-run relationships and short-run dynamics

According to the test results from the preceding section, we proceed to estimate the long-run elasticities and the corresponding error correction models for ten of the twelve initially considered countries, viz. Austria, Finland, Germany, Ireland, Japan, Luxembourg, the Netherlands, Switzerland, the UK, and the US.

As described in Section 3, for each country a model is specified according to Eq. (5). The model selection is guided by the Akaike Information Criterion (AIC) and the Schwarz Bayesian Criterion (SBC). Furthermore, we make sure that the residuals are not serially correlated. The resulting parameter estimates are used to construct the long-run elasticities according to Eqs. (6)–(8). Finally, in order to obtain the short-run dynamics, the corresponding error correction models given in Eq. (9) are estimated using the lagged *ECT*s resulting from the long-run relationships estimated.

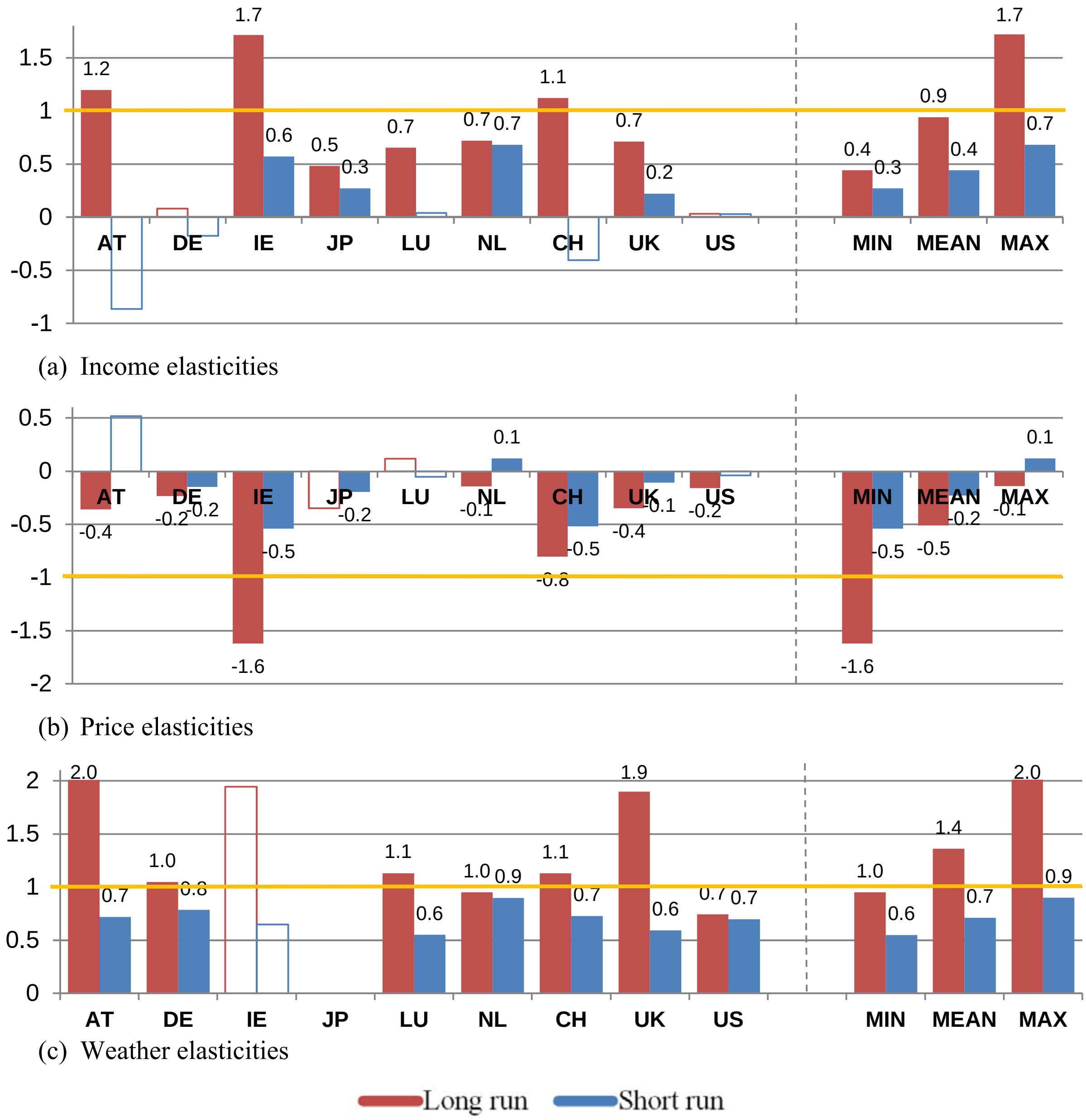
Fig. 5 summarizes the estimated demand elasticities with regard to income (a), price (b) and weather (c).

With more details, Tables 6–8 summarize the estimated long-run coefficients, the error correction estimation results and the diagnostic tests (for serial correlation, normality, and heteroscedasticity) of the underlying ARDL models for the individual countries, respectively.[7]

The order of the individual country-specific ARDLs and the specification with regard to the deterministic term are given in Table 6, along with the estimated long-run coefficients and the corresponding *p*-values. As expected, the signs of the statistically significant income and price elasticities are positive and negative, respectively. The country estimates of long-run income elasticity range between 0.44 for Japan and 1.72 for Ireland, with a near-unity mean of 0.94. The estimates of long-run price elasticity range between –1.62 for Ireland and –0.14 for the Netherlands, with a mean of –0.51. The long-run elasticities with regard to heating degree days range between 0.95 for the Netherlands and 2.01 for Austria with a mean of 1.36.

As a robustness check, we make use of two further well-established estimation methods for estimating the long-run relationship characterized by Eq. (2). These are the dynamic OLS

[7] Tests on constancy of the cointegration space are delivered in Section 4.4.



(a) Income elasticities

(b) Price elasticities

(c) Weather elasticities

Fig. 5: Elasticity estimates (Transparent bars indicate estimates not significant at conventional levels)

(DOLS) from Saikkonen (1992) and Stock and Watson (1993), and the fully modified OLS (FMOLS) from Phillips and Hansen (1990). Both estimators incorporate corrections for endogeneity bias and serial correlation in a parametric and semi-parametric way, respectively. The results can be found in Table A.2 in the appendix. Comparing the long-run coefficient estimates from all three estimation procedures one finds agreement with regard to the signs of the coefficients whenever the estimates are significantly different from zero. The estimates for most countries are in the same range of magnitude, with only few exceptions. Overall, we can conclude that the results are fairly robust with regard to the estimation method employed.

The coefficient estimates of the error-correction models are presented in Table 10. The speeds of adjustment toward long-run equilibria range between an annual correction of 31% in the UK and 96% in the US. On average, 57% of any deviation from the long-run equilibrium is corrected every year. Hence, a near complete adjustment (of at least 95%) is achieved after

Table 6
Long-run coefficients for country-specific ARDLs

Country Order of ARDL	**Long-run coefficients**				
	y	*p*	*hdd*	*Trend*	*Constant*
Austria ARDL(1,2,2,0)	1.196** [0.021]	–0.360** [0.045]	2.007** [0.014]	–	–18.259*** [0.008]
Finland ARDL(1,1,0,0)	0.797 [0.127]	–0.267 [0.214]	0.551 [0.742]	–	–12.250 [0.357]
Germany ARDL(2,1,1,1)	0.080 [0.904]	–0.233** [0.011]	1.047*** [0.003]	0.043*** [0.000]	–15.541*** [0.000]
Ireland ARDL(1,0,0,0)	1.715*** [0.001]	–1.621** [0.021]	1.945 [0.500]	–	–7.607 [0.700]
Japan ARDL(1,0,0)	0.482** [0.039]	–0.350 [0.110]	–	0.009*** [0.001]	–5.551*** [0.000]
Luxembourg ARDL(1,1,1,0)	0.653*** [0.000]	0.117 [0.228]	1.131** [0.041]	–	–15.160*** [0.001]
Netherlands ARDL(1,0,1,0)	0.720*** [0.005]	–0.144*** [0.000]	0.950*** [0.000]	–0.022*** [0.000]	–10.941*** [0.000]
Switzerland ARDL(1,2,0,0)	1.121** [0.012]	–0.804*** [0.000]	1.129*** [0.001]	0.026*** [0.000]	–9.861*** [0.000]
UK ARDL(1,0,0,0)	0.711*** [0.000]	–0.350** [0.014]	1.897** [0.028]	–	–18.048*** [0.004]
US ARDL(1,0,1,0)	0.031 [0.807]	–0.159*** [0.000]	0.743*** [0.000]	–0.006*** [0.005]	–12.865*** [0.000]
MIN	0.44	–1.62	0.95		
MEAN	**0.94**	**–0.51**	**1.36**		
MAX	1.72	–0.14	2.01		

Notes: ***, ** and * denote significance at the 1%, 5% and 10% level, respectively. *p*-values are reported in brackets. MIN, MEAN and MAX values refer to significant estimates only. Moreover, Finland is not included on account of model deficiencies.

Table 7

Error correction representations for the underlying ARDL models

Country	Short-run dynamics							
	ECT_{t-1}	Δg_{t-1}	Δy_t	Δy_{t-1}	Δp_t	Δp_{t-1}	Δhdd_t	$\Delta Trend$
Austria	–0.358*** [0.004]	–	–0.864 [0.241]	–0.634 [0.432]	0.517 [0.505]	0.185 [0.126]	0.719*** [0.002]	–
Finland	–0.541*** [0.001]	–	–1.831** [0.047]	–	–0.145 [0.216]	–	0.298 [0.742]	–
Germany	–0.593** [0.045]	–0.050 [0.672]	–0.175 [0.681]	–	–0.150** [0.043]	–	0.786*** [0.000]	0.025* [0.062]
Ireland	–0.334** [0.030]	–	0.572* [0.065]	–	–0.541*** [0.001]	–	0.649 [0.433]	–
Japan	–0.561*** [0.001]	–	0.271* [0.073]	–	–0.196* [0.081]	–	–	0.005** [0.034]
Luxembourg	–0.487*** [0.004]	–	0.038 [0.870]	–	–0.053 [0.446]	–	0.551*** [0.002]	–
Netherlands	–0.945*** [0.000]	–	0.681*** [0.007]	–	0.119* [0.079]	–	0.898*** [0.000]	–0.021*** [0.000]
Switzerland	–0.644*** [0.000]	–	–0.404 [0.139]	–0.635* [0.073]	–0.518*** [0.000]	–	0.727*** [0.000]	0.017*** [0.001]
UK	–0.312*** [0.004]	–	0.222*** [0.001]	–	–0.109** [0.010]	–	0.592*** [0.000]	–
US	–0.940*** [0.000]	–	0.029 [0.807]	–	–0.041 [0.350]	–	0.698*** [0.000]	–0.005*** [0.007]
MIN	–0.31		0.27		–0.54		0.55	
MEAN	**–0.57**		**0.44**		**–0.23**		**0.71**	
MAX	–0.96		0.68		0.12		0.90	

Notes: ***, ** and * denote significance at the 1%, 5% and 10% level, respectively. *p*-values are reported in brackets. MIN, MEAN and MAX values refer to significant estimates only. Moreover, Finland is not included on account of model deficiencies.

three to four years on average. The short-run elasticities with regard to income, price and heating degree days are generally lower in magnitude than their long-run counterparts. Short-run income elasticities range between 0.27 for Japan and 0.68 for the Netherlands, with an average of 0.44. The short-run price elasticities range between –0.54 for Ireland and 0.12 for the Netherlands, with a mean of –0.23. Finally, the short-run coefficients for heating degree days range between 0.55 for Luxembourg and 0.90 for the Netherlands, with an average of 0.71. Hence, on average, the short-run elasticities have approximately half the magnitude of their long-run counterparts.

Comparing our results with the estimates from other studies on residential natural gas demand (given in Table 3), we find considerable differences, which to some extent are due to the respective time spans analyzed and econometric approaches used. Particularly, the disregard of problems related to the potential non-stationarity of the underlying time series casts doubts on the reliability of the results generated by the aforementioned studies.

- For a group of 12 EU member countries Asche *et al.* (2008) find long-run elasticities of 3.32 and –0.10 with regard to income and price. Our estimates, although not for exactly the same country group[8], are much less extreme in magnitude. Our average income elasticity is 0.94, while the average price elasticity is –0.51. Regarding the short-run elasticities differences still remain, but are less pronounced: Asche *et al.* find 0.81 (–0.03), while we find 0.44 (–0.23) for income (price).

- Berkhout *et al.* (2004) find elasticities of –0.27 with regard to income and –0.19 with regard to price (the latter not significant) for the Netherlands. A negative income elasticity is rather counterintuitive. Hence, our elasticity estimates, 0.72 for income and –0.14 for price, seem more sensible based on economic grounds.

- The results from Joutz *et al.* (2008) and Lin *et al.* (1987) for long- and short-run elasticities with regard to price in the US are fairly contradictive. While Joutz *et al.* find a long-run elasticity of –0.18, which is close to our point estimate (–0.16), Lin *et al.* find a rather large (in magnitude) elasticity of –1.22. For the short run, the elasticities from both studies are rather small (–0.09 and –0.15, respectively), while ours is not significantly different from zero.

[8] While our sample does not include Belgium, Denmark and Italy, their sample does not include Japan and the US. Moreover, our sample covers a longer time span: 1978 until 2008 instead of up to 2002.

Table 8 summarizes a set of diagnostic test statistics for the individual ARDL models. The tests indicate problems with the assumptions of no serial correlation, normality and homoscedasticity of the residuals in the model for Finland. Furthermore, the models for Ireland and the UK have deficiencies with regard to normality and homoscedasticity of the residuals, respectively. For all other models the tests show no deviations from theoretical model assumptions.

Table 8
Diagnostic tests for the underlying ARDL models

Country	Lagrange multiplier statistics		
	Serial correlation: $\chi^2_{SC}(1)$	Normality: $\chi^2_N(2)$	Heteroscedasticity: $\chi^2_H(1)$
Austria	0.149 [0.699]	1.094 [0.579]	3.315 [0.069]
Finland	3.410 [0.065]	21.215 [0.000]	3.963 [0.047]
Germany	1.941 [0.164]	1.880 [0.391]	0.208 [0.649]
Ireland	0.270 [0.604]	16.694 [0.000]	2.665 [0.103]
Japan	2.677 [0.102]	1.525 [0.466]	2.035 [0.154]
Luxembourg	0.252 [0.616]	1.716 [0.424]	0.000 [0.993]
Netherlands	0.139 [0.709]	0.494 [0.781]	2.141 [0.143]
Switzerland	0.006 [0.938]	0.211 [0.900]	5.665 [0.017]
UK	0.677 [0.411]	0.065 [0.798]	9.197 [0.010]
US	2.404 [0.121]	1.169 [0.557]	0.292 [0.589]

Notes: p-values are reported in brackets.

4.4. Constancy of cointegration space

In order to check for parameter constancy, we employ the CUSUM and the CUSUMSQ stability tests (see Brown *et al.*, 1975) to the estimated ARDL model of each country.

The CUSUM and CUSUMSQ plots for each model are shown in Figure 6, plots (a)–(j). As can be seen, the plots are within the 5% critical bounds in all the models, except for the case of Japan. Here the CUSUMSQ plot crosses the upper critical bound, indicating some instability of the estimated coefficients in the years 1993 to 1997. For all other models the stability tests show an overall constancy of the cointegration space.

5. Conclusions

In this paper we have analyzed residential natural gas demand for twelve OECD countries using available time series data from 1980 to 2008. We estimate long-run demand elasticities with regard to real disposable income and real residential natural gas price using the autoregressive distributed lag (ARDL) bounds testing procedure developed by Pesaran and Shin (1999) and Pesaran *et al.* (2001). In contrast to other cointegration approaches, this procedure has the advantage of needing no pretesting on the time series properties of the single variables, and thereby circumventing the problem associated with the low power of unit root tests. By employing an error correction framework we also obtain estimates for the speeds of adjustment to long-run equilibrium and short-run elasticities for the individual countries. The effect of weather conditions on natural gas demand in a given year is accounted for by including heating degree days as a control variable.

For ten of the twelve countries we find a significant long-run relationship. On average, the long-run elasticities are 0.94 with regard to income, –0.51 with regard to price and 1.36 with regard to heating degree days. For the individual countries, the long-run income elasticities range between 0.44 for Japan and 1.72 for Ireland, while the long-run price elasticities range between –1.62 for Ireland and –0.14 for the Netherlands. The long-run elasticities with regard to heating degree days are found to be between 0.95 for the Netherlands and 2.01 for Austria.

The short-run dynamics assessed by estimation of the error correction models indicate an average adjustment coefficient of –0.57, a short-run income elasticity of 0.44, a short-run price elasticity of –0.23 and a short-run elasticity with regard to heating degree days of 0.71. Hence, on average, the short-run elasticities have approximately half the magnitude of their long-run counterparts.

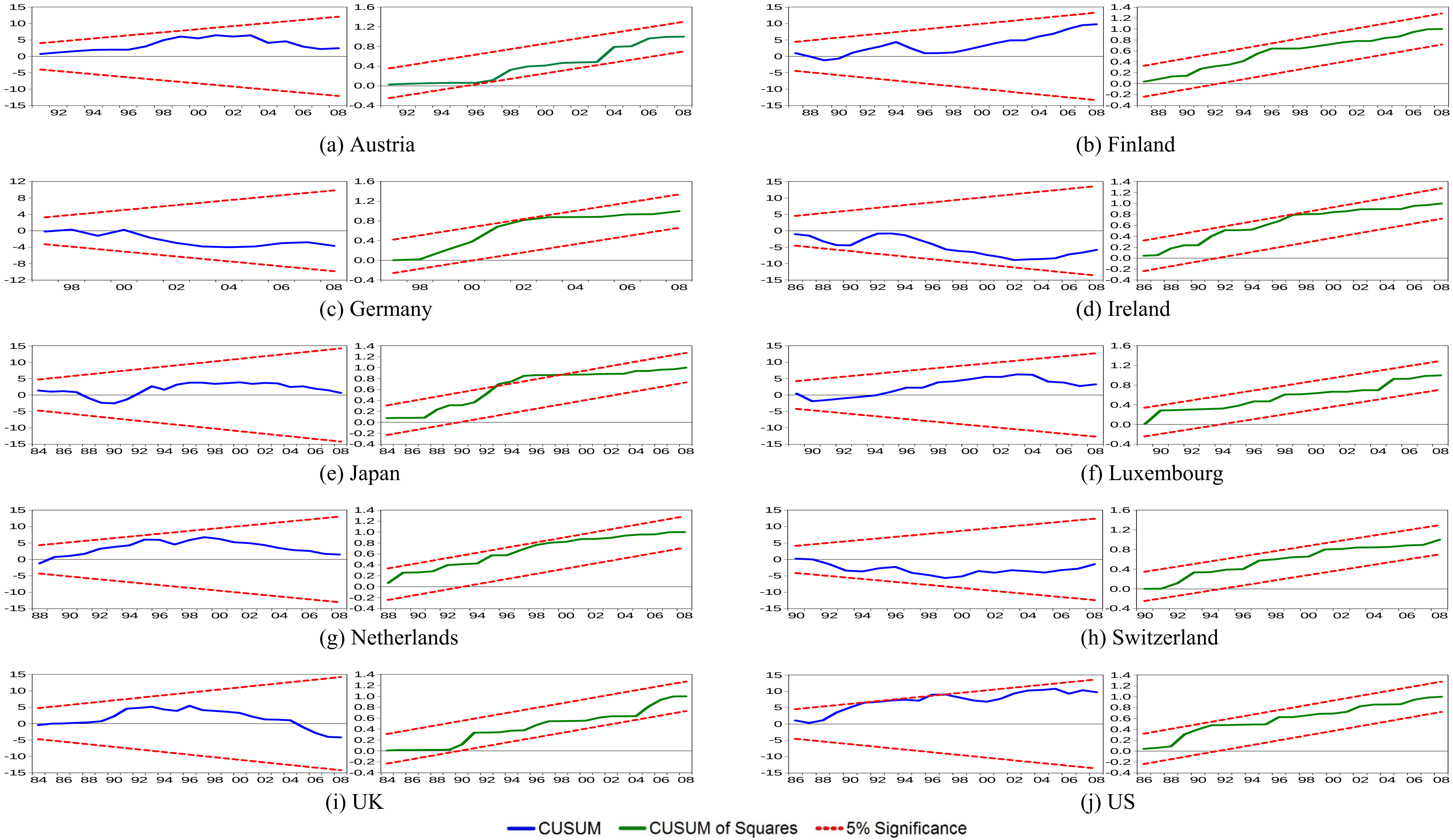


Fig. 6: CUSUM and CUSUM of squares plots for the estimated ARDL models

References

Asche, F., Nilsen, O.B., Tveteras, R. (2008). Natural gas demand in the European household sector. *The Energy Journal* **29**(3): 27–46.

Berkhout, P.H.G., Ferrer-i-Carbonell, A., Muskens, J.C. (2004). The ex post impact of an energy tax on household energy demand. *Energy Economics* **26**(3): 297–317.

Brown, R. L., J. Durbin, and J. M. Evans (1975). Techniques for testing the constancy of regression relationships over time. *Journal of the Royal Statistical Society. Series B (Methodolgical)* **37**(2): 149–192.

Elliott, G., Rothenberg, T.J., Stock, J.H. (1996). Efficient tests for an autoregressive unit root. *Econometrica* **64**(4): 813–836.

International Energy Agency (2011). *World Energy Outlook 2010*. Paris, France.

Joutz, F.L., Shin, D., McDowell, B., Trost, R.P. (2008). Estimating regional short-run and long-run price elasticities of residential natural gas demand in the U.S., 28th USAEE/IAEE Annual North American Conference, New Orleans, LA, December 3–5.

Lin, W.T., Chen, Y.H., Chatov R. (1987). The demand for natural gas, electricity and heating oil in the United States. *Resources and Energy* **9**(3): 233–258.

MacKinnon, J.G. (1996). Numerical distribution functions for unit root and cointegration tests. *Journal of Applied Econometrics* **11**(6): 601–618.

Pesaran, P., Pesaran, M.H., (2009). *Time series econometrics using Microfit 5.0*. Oxford University Press, Oxford.

Pesaran, M.H., Shin, Y. (1999). An autoregressive distributed-lag modelling approach to cointegration analysis. In: Strom, S. (Ed.), *Econometrics and Economic Theory in the 20th Century*. Cambridge University Press, Cambridge.

Pesaran, M.H., Shin, Y., Smith, R.J. (2001). Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics* **16**(3): 289–326.

Phillips, P.C.B, Hansen, B.E. (1990). Statistical inference in instrumental variables regression with I(1) processes. *Review of Economic Studies* **57**(1): 99–125.

Saikkonen, P. (1992). Estimation and testing of cointegrated systems by an autoregressive approximation. *Econometric Theory* **8**(1): 1–27.

Stock, J.H., Watson, M.W. (1993). A simple estimator of cointegrating vectors in higher order integrated systems. *Econometrica* **61**(4): 783–820.

Appendix

Table A.1
Unit root test (ERS) on first differences (Δ) of individual variables

Country	Δg	Δy	Δp	Δhdd
Austria	–2.764*** (1)	–3.414*** (1)	–2.311** (2)	–4.123*** (1)
Finland	–4.061*** (0)	–2.774*** (0)	–3.289*** (1)	–7.323*** (0)
Germany	–5.621*** (0)	–3.431*** (0)	–3.996*** (0)	–6.627*** (0)
Ireland	–2.154** (2)	–1.709* (1)	–3.500*** (2)	–3.751*** (1)
Japan	–3.037*** (1)	–2.345** (0)	–4.729*** (0)	———
Luxembourg	–2.873*** (1)	–4.151*** (1)	–4.430*** (0)	–6.480*** (0)
Netherlands	–3.534*** (1)	–4.135*** (0)	–3.685*** (0)	–6.362*** (0)
Switzerland	–2.301** (1)	–2.725*** (0)	–3.135*** (0)	–7.006*** (0)
UK	–4.171*** (0)	–2.986*** (0)	–1.750* (1)	–3.061*** (1)
US	–6.378*** (0)	–2.845*** (0)	–2.321** (3)	–6.127*** (0)

Notes: Null hypothesis: Δg has a unit root. Critical values are from MacKinnon (1996): 1% = –2.653; 5% = –1.964; 10% = –1.610. Lag lengths are in parentheses.

Table A.2
Comparison of long-run coefficients from different estimation methods

Country	Long-run coefficients				
	y	*p*	*hdd*	*Trend*	*Constant*
Austria					
ARDL	1.196** [0.021]	–0.360** [0.045]	2.007** [0.014]	–	–18.259** [0.008]
DOLS	1.646*** [0.004]	–0.231 [0.152]	0.946 [0.547]	–	–8.701 [0.462]
FMOLS	1.836*** [0.000]	–0.488*** [0.000]	0.669* [0.096]	–	–4.207 [0.152]
Germany					
ARDL	0.080 [0.904]	–0.233** [0.011]	1.047*** [0.003]	0.043*** [0.000]	–15.541*** [0.000]
DOLS	0.120 [0.795]	–0.201** [0.023]	1.037*** [0.001]	0.041*** [0.000]	–15.450*** [0.000]
FMOLS	–0.320 [0.310]	–0.199*** [0.000]	0.844*** [0.000]	0.045*** [0.000]	–15.669*** [0.000]
Ireland					
ARDL	1.715*** [0.001]	–1.621** [0.021]	1.945 [0.500]	–	–7.607 [0.700]
DOLS	1.123*** [0.000]	–1.568*** [0.000]	–	–	4.931*** [0.001]
FMOLS	1.614*** [0.000]	–0.712*** [0.008]	–1.439 [0.312]	–	12.923 [0.215]
Japan					
ARDL	0.482** [0.039]	–0.350 [0.110]	–	0.009*** [0.001]	–5.551*** [0.000]
DOLS	0.426** [0.011]	–0.400** [0.017]	–	0.009*** [0.000]	–5.368*** [0.000]
FMOLS	0.411*** [0.006]	–0.344** [0.016]	–	0.009*** [0.000]	–5.750*** [0.000]
Luxembourg					
ARDL	0.653*** [0.000]	0.117 [0.228]	1.131** [0.041]	–	–15.160*** [0.001]
DOLS	0.643*** [0.000]	0.113 [0.220]	0.776 [0.155]	–	–12.325*** [0.005]
FMOLS	0.613*** [0.000]	–0.038 [0.500]	0.556** [0.021]	–	–9.828*** [0.000]
Netherlands					
ARDL	0.720*** [0.005]	–0.144*** [0.000]	0.950*** [0.000]	–0.022*** [0.000]	–10.941*** [0.000]
DOLS	1.079*** [0.000]	–0.191*** [0.000]	1.022*** [0.000]	–0.029*** [0.000]	–9.743*** [0.000]
FMOLS	1.226*** [0.000]	–0.158*** [0.001]	0.921*** [0.000]	–0.033*** [0.000]	–8.472*** [0.000]
Switzerland					
ARDL	1.121** [0.012]	–0.804*** [0.000]	1.129*** [0.001]	0.026*** [0.000]	–9.861*** [0.000]
DOLS	0.956** [0.014]	–0.760*** [0.000]	0.471 [0.267]	0.027*** [0.000]	–5.377* [0.099]
FMOLS	0.252 [0.374]	–0.730*** [0.000]	0.443** [0.045]	0.034*** [0.000]	–7.903*** [0.000]
UK					
ARDL	0.711*** [0.000]	–0.350** [0.014]	1.897** [0.028]	–	–18.048*** [0.004]
DOLS	0.569*** [0.000]	–0.311** [0.019]	1.132* [0.080]	–	–12.663*** [0.008]
FMOLS	0.500*** [0.000]	–0.303*** [0.000]	0.633*** [0.000]	–	–9.020*** [0.000]
US					
ARDL	0.031 [0.807]	–0.159*** [0.000]	0.743*** [0.000]	–0.006*** [0.005]	–12.865*** [0.000]
DOLS	0.194 [0.230]	–0.161*** [0.000]	0.785*** [0.000]	–0.008*** [0.003]	–12.598*** [0.000]
FMOLS	0.103 [0.234]	–0.153* [0.000]	0.736*** [0.000]	–0.007*** [0.000]	–12.581*** [0.000]

Notes: ***, ** and * denote significance at the 1%, 5% and 10% level, respectively. *p*-values are reported in brackets.

List of FCN Working Papers

2011

Sorda G., Sunak Y., Madlener R. (2011). A Spatial MAS Simulation to Evaluate the Promotion of Electricity from Agricultural Biogas Plants in Germany, FCN Working Paper No. 1/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, January.

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Madlener R., Glensk B., Weber V. (2011). Fuzzy Portfolio Optimization of Onshore Wind Power Plants. FCN Working Paper No. 10/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May.

Glensk B., Madlener R. (2011). Portfolio Selection Methods and their Empirical Applicability to Real Assets in Energy Markets. FCN Working Paper No. 11/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May.

Kraas B., Schroedter-Homscheidt M., Pulvermüller B., Madlener R. (2011). Economic Assessment of a Concentrating Solar Power Forecasting System for Participation in the Spanish Electricity Market, FCN Working Paper No. 12/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May.

Stocker A., Großmann A., Madlener R., Wolter M.I., (2011). Sustainable Energy Development in Austria Until 2020: Insights from Applying the Integrated Model “e3.at”, FCN Working Paper No. 13/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, July.

Kumbaroğlu G., Madlener R. (2011). Evaluation of Economically Optimal Retrofit Investment Options for Energy Savings in Buildings. FCN Working Paper No. 14/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

Bernstein R., Madlener R. (2011). Residential Natural Gas Demand Elasticities in OECD Countries: An ARDL Bounds Testing Approach, FCN Working Paper No. 15/2011, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, October.

2010

Lang J., Madlener R. (2010). Relevance of Risk Capital and Margining for the Valuation of Power Plants: Cash Requirements for Credit Risk Mitigation, FCN Working Paper No. 1/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, February.

Michelsen C., Madlener R. (2010). Integrated Theoretical Framework for a Homeowner's Decision in Favor of an Innovative Residential Heating System, FCN Working Paper No. 2/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, February.

Harmsen - van Hout M.J.W., Herings P.J.-J., Dellaert B.G.C. (2010). The Structure of Online Consumer Communication Networks, FCN Working Paper No. 3/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, March.

Madlener R., Neustadt I. (2010). Renewable Energy Policy in the Presence of Innovation: Does Government Pre-Commitment Matter?, FCN Working Paper No. 4/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, April (revised June 2010 and December 2011).

Harmsen-van Hout M.J.W., Dellaert B.G.C., Herings, P.J.-J. (2010). Behavioral Effects in Individual Decisions of Network Formation: Complexity Reduces Payoff Orientation and Social Preferences, FCN Working Paper No. 5/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, May.

Lohwasser R., Madlener R. (2010). Relating R&D and Investment Policies to CCS Market Diffusion Through Two-Factor Learning, FCN Working Paper No. 6/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, June.

Rohlfs W., Madlener R. (2010). Valuation of CCS-Ready Coal-Fired Power Plants: A Multi-Dimensional Real Options Approach, FCN Working Paper No. 7/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, July.

Rohlfs W., Madlener R. (2010). Cost Effectiveness of Carbon Capture-Ready Coal Power Plants with Delayed Retrofit, FCN Working Paper No. 8/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August (revised December 2010).

Gampert M., Madlener R. (2010). Pan-European Management of Electricity Portfolios: Risks and Opportunities of Contract Bundling, FCN Working Paper No. 9/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

Glensk B., Madlener R. (2010). Fuzzy Portfolio Optimization for Power Generation Assets, FCN Working Paper No. 10/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

Lang J., Madlener R. (2010). Portfolio Optimization for Power Plants: The Impact of Credit Risk Mitigation and Margining, FCN Working Paper No. 11/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

Westner G., Madlener R. (2010). Investment in New Power Generation Under Uncertainty: Benefits of CHP vs. Condensing Plants in a Copula-Based Analysis, FCN Working Paper No. 12/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

Bellmann E., Lang J., Madlener R. (2010). Cost Evaluation of Credit Risk Securitization in the Electricity Industry: Credit Default Acceptance vs. Margining Costs, FCN Working Paper No. 13/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September (revised May 2011).

Ernst C.-S., Lunz B., Hackbarth A., Madlener R., Sauer D.-U., Eckstein L. (2010). Optimal Battery Size for Serial Plug-in Hybrid Vehicles: A Model-Based Economic Analysis for Germany, FCN Working Paper No. 14/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, October (revised June 2011).

Harmsen - van Hout M.J.W., Herings P.J.-J., Dellaert B.G.C. (2010). Communication Network Formation with Link Specificity and Value Transferability, FCN Working Paper No. 15/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Paulun T., Feess E., Madlener R. (2010). Why Higher Price Sensitivity of Consumers May Increase Average Prices: An Analysis of the European Electricity Market, FCN Working Paper No. 16/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Madlener R., Glensk B. (2010). Portfolio Impact of New Power Generation Investments of E.ON in Germany, Sweden and the UK, FCN Working Paper No. 17/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Ghosh G., Kwasnica A., Shortle J. (2010). A Laboratory Experiment to Compare Two Market Institutions for Emissions Trading, FCN Working Paper No. 18/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Bernstein R., Madlener R. (2010). Short- and Long-Run Electricity Demand Elasticities at the Subsectoral Level: A Cointegration Analysis for German Manufacturing Industries, FCN Working Paper No. 19/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Mazur C., Madlener R. (2010). Impact of Plug-in Hybrid Electric Vehicles and Charging Regimes on Power Generation Costs and Emissions in Germany, FCN Working Paper No. 20/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Madlener R., Stoverink S. (2010). Power Plant Investments in the Turkish Electricity Sector: A Real Options Approach Taking into Account Market Liberalization, FCN Working Paper No. 21/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Melchior T., Madlener R. (2010). Economic Evaluation of IGCC Plants with Hot Gas Cleaning, FCN Working Paper No. 22/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Lüschen A., Madlener R. (2010). Economics of Biomass Co-Firing in New Hard Coal Power Plants in Germany, FCN Working Paper No. 23/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Madlener R., Tomm V. (2010). Electricity Consumption of an Ageing Society: Empirical Evidence from a Swiss Household Survey, FCN Working Paper No. 24/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Tomm V., Madlener R. (2010). Appliance Endowment and User Behaviour by Age Group: Insights from a Swiss Micro-Survey on Residential Electricity Demand, FCN Working Paper No. 25/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Hinrichs H., Madlener R., Pearson P. (2010). Liberalisation of Germany's Electricity System and the Ways Forward of the Unbundling Process: A Historical Perspective and an Outlook, FCN Working Paper No. 26/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Achtnicht M. (2010). Do Environmental Benefits Matter? A Choice Experiment Among House Owners in Germany, FCN Working Paper No. 27/2010, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

2009

Madlener R., Mathar T. (2009). Development Trends and Economics of Concentrating Solar Power Generation Technologies: A Comparative Analysis, FCN Working Paper No. 1/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Madlener R., Latz J. (2009). Centralized and Integrated Decentralized Compressed Air Energy Storage for Enhanced Grid Integration of Wind Power, FCN Working Paper No. 2/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November (revised September 2010).

Kraemer C., Madlener R. (2009). Using Fuzzy Real Options Valuation for Assessing Investments in NGCC and CCS Energy Conversion Technology, FCN Working Paper No. 3/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Westner G., Madlener R. (2009). Development of Cogeneration in Germany: A Dynamic Portfolio Analysis Based on the New Regulatory Framework, FCN Working Paper No. 4/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November (revised March 2010).

Westner G., Madlener R. (2009). The Benefit of Regional Diversification of Cogeneration Investments in Europe: A Mean-Variance Portfolio Analysis, FCN Working Paper No. 5/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November (revised March 2010).

Lohwasser R., Madlener R. (2009). Simulation of the European Electricity Market and CCS Development with the HECTOR Model, FCN Working Paper No. 6/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Lohwasser R., Madlener R. (2009). Impact of CCS on the Economics of Coal-Fired Power Plants – Why Investment Costs Do and Efficiency Doesn't Matter, FCN Working Paper No. 7/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Holtermann T., Madlener R. (2009). Assessment of the Technological Development and Economic Potential of Photobioreactors, FCN Working Paper No. 8/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Ghosh G., Carriazo F. (2009). A Comparison of Three Methods of Estimation in the Context of Spatial Modeling, FCN Working Paper No. 9/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Ghosh G., Shortle J. (2009). Water Quality Trading when Nonpoint Pollution Loads are Stochastic, FCN Working Paper No. 10/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Ghosh G., Ribaudo M., Shortle J. (2009). Do Baseline Requirements hinder Trades in Water Quality Trading Programs?, FCN Working Paper No. 11/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

Madlener R., Glensk B., Raymond P. (2009). Investigation of E.ON's Power Generation Assets by Using Mean-Variance Portfolio Analysis, FCN Working Paper No. 12/2009, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, November.

2008

Madlener R., Gao W., Neustadt I., Zweifel P. (2008). Promoting Renewable Electricity Generation in Imperfect Markets: Price vs. Quantity Policies, FCN Working Paper No. 1/2008, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, July (revised May 2009).

Madlener R., Wenk C. (2008). Efficient Investment Portfolios for the Swiss Electricity Supply Sector, FCN Working Paper No. 2/2008, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

Omann I., Kowalski K., Bohunovsky L., Madlener R., Stagl S. (2008). The Influence of Social Preferences on Multi-Criteria Evaluation of Energy Scenarios, FCN Working Paper No. 3/2008, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, August.

Bernstein R., Madlener R. (2008). The Impact of Disaggregated ICT Capital on Electricity Intensity of Production: Econometric Analysis of Major European Industries, FCN Working Paper No. 4/2008, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

Erber G., Madlener R. (2008). Impact of ICT and Human Skills on the European Financial Intermediation Sector, FCN Working Paper No. 5/2008, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, September.

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