Does economic growth drive energy consumption in Madagascar? Fresh empirical evidence

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Abstract

This study uses quarterly data spanning from 2007 to 2022 to examine the long-run relationship and causal nexus between economic growth and energy consumption in Madagascar, disaggregating energy consumption into electricity and petroleum consumption, as well as considering total energy consumption, while accounting for the impact of energy imports and energy prices within an econometric framework. Using the Bayer-Hanck cointegration test, we found evidence of positive long-run relationships between the variables of interest. Furthermore, we estimated the long-run elasticities using three complementary approaches: the Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegrating Regression (CCR) estimators. The empirical findings indicate that economic growth, energy imports, and energy prices have a positive and statistically significant impact on energy consumption in Madagascar. Additionally, we employed the Toda-Yamamoto approach to Granger non-causality test and the Breitung-Candelon frequency-domain test to investigate the causal relationships among the variables. Notably, our results reveal a unidirectional long-run Granger-causality flowing from economic growth to electricity consumption, thereby providing support for the conservation hypothesis. Furthermore, the time-domain causality test reveals a neutral relationship between economic growth and petroleum consumption, as well as total energy consumption, which is consistent with the neutrality hypothesis. However, the Breitung-Candelon test uncovers a more nuanced dynamic, with total energy consumption found to Granger-cause economic growth in both the long and medium run, thereby supporting the growth hypothesis. Notably, the causal linkage is strengthened when the test is not conditioned on energy prices and energy imports, and petroleum consumption is also found to cause economic growth in this bivariate framework. Conversely, electricity and economic growth become neutral to each other. Our findings highlight the intricate interplay between economic growth and energy consumption, underscoring the critical roles of energy imports and prices in this dynamic.

Keywords: economic growth, energy consumption, electricity consumption, petroleum consumption, energy imports, energy prices, causal nexus, Madagascar

Disclaimer. The views presented in this working paper are solely those of the author and do not necessarily reflect the positions of his affiliation. The author are responsible for any errors in the paper.

1 Introduction

The nexus between economic growth and energy consumption is a hot topic in energy economics (Ozturk, 2010; Tiba and Omri, 2017; Jakovac, 2018; Mutumba et al., 2021). For Madagascar particularly, there is a notable scarcity of empirical literature on this topic. Notable exceptions include the work of Voninirina and Andriambelosoa (2014) and Andriamanga (2017). This study aims to bridge this knowledge gap by building upon the recent work of Ramaharo et al. (2024), who investigated the impact of energy demand on economic growth. Our paper explores the converse relationship, examining the effect of economic growth on energy demand. We use the standard energy demand function which links economic growth and energy prices to energy consumption (Al-Azzam and Hawdon, 1999; Asafu-Adjaye, 2000; De Vita et al., 2006; Hatemi-J and Irandoust, 2005; Amarawickrama and Hunt, 2008; Amusa et al., 2009; Iwayemi et al., 2010; Weixian, 2002; Odhiambo, 2010; Belke et al., 2011; Hossein et al., 2012; Tang and Tan, 2013; Pinzón, 2016; Sharmin and Khan, 2016; Carfora et al., 2019; Wang et al., 2019), and to which we add energy imports (Sadorsky, 2011; Mitchel, 2006; Murshed, 2021). Given Madagascar's traditional reliance on importing primary energy resources, including petroleum products, coal, and fuel wood (Rafitoson, 2017; MEH, 2019; Subtil, 2021), it is crucial to account for the impact of energy import dependency on energy demand (Damette and Marques, 2018; Murshed and Tanha, 2021). Hence, the energy demand function is described as

$$e_t = f(y_t, m_t, p_t), \tag{1}$$

where e_t represents energy consumption, y_t denotes economic growth, m_t represents energy imports, and p_t denotes energy prices. The primary objective of this paper is to explore the long-run relationship between economic growth and energy demand in Madagascar, by deriving both disaggregated and aggregated econometric models from (1). Specifically, we examine energy consumption in the form of electricity and petroleum products, as well as total energy consumption, which comprises both of these energy sources. To achieve this econometric analysis, we use quarterly data covering the period of 2007 to 2022. Each model will be tested for cointegration and then estimated, and the causal relationships between economic growth and each form of energy consumption will be examined. The subsequent sections present the methodology employed and discuss the empirical findings, which aim to provide insights into the dynamics of energy consumption in Madagascar and inform policy decisions related to energy management and economic growth.

2 Empirical methodology and results

2.1 Data sources and construction

This study employs quarterly data spanning from 2007 to 2024, sourced from various institutions, including the National Institute of Statistics (INSTAT, 2019, 2021, 2024), the Malagasy Office of Hydrocarbons (OMH, 2024), the Office of Electricity Regulation (ORE, 2024), and the Malagasy Customs (Douane Malagasy, 2024). Additionally, data on the global brent crude price were obtained from the Federal Reserve Economic Data (FRED, 2024). Data are summarized in Table 1.

Prior to econometric analysis, the raw data were seasonally adjusted using the ARIMA X11 methodology and transformed into logarithmic form to ensure homoscedasticity. Note that final energy consumption in Madagascar encompasses biofuels, fossil fuels, petroleum products, and electricity (MEH, 2019). However, our analysis focuses on petroleum products and electricity, as these are the only categories with available quarterly data, serving as a proxy for energy consumption. We calculate total energy consumption by aggregating electricity consumption and petroleum product consumption, with both converted into millions of British thermal units (Btu) using standard energy equivalence factors (CEC, 2024). As a result, petroleum products constitute the dominant energy source in our analysis, accounting for approximately 90% of total energy consumption, while electricity consumption makes up the remaining 10%. Next, we apply principal component analysis (PCA) to the energy consumer price index (normalized to 2007 = 100), the imports price index, and the global price of Brent crude oil (also converted to an index with 2007 = 100).

We assess the suitability of the data for PCA using the Kaiser-Meyer-Olkin (KMO) statistic (Kaiser, 1974) and Bartlett's test of sphericity (Bartlett, 1951). The KMO statistic is a measure of sampling adequacy (MSA) of each observed variables in the model as well as the complete model, and an overall KMO value above 0.50 is recommended before proceeding with factor analysis (Hair et al., 2018, p. 136). Bartlett's test of sphericity is used to test the null hypothesis that the original correlation matrix is an identity matrix, meaning the variables are uncorrelated. A low p-value (typically less than 0.05) from Bartlett's test indicates sufficient correlations between the variables, making PCA appropriate.

The results of the KMO and Bartlett tests are reported in Table 2. The value of the KMO statistic is 0.568, which is above the minimum threshold of 0.5, indicating the suitability of the PCA for the sample.

Table 1: Data and variable definition

Variables	Symbol	Proxy and unit of measurement	Data sources
Economic growth	GDP	Real gross domestic product in billions of Ariary, at 2007 constant prices	INSTAT
Electricity consumption	ELC	Total electricity consumption: sum of low voltage (residential) and medium voltage (agriculture, industry, service, residential) electricity consumption, in kWh	ORE, INSTAT
Petroleum consumption	PEC	Total petroleum consumption: sum of naphtha, jet fuel, aviation fuel, liquefied petroleum gas, kerosene, super-unleaded petrol, gasoline, gas oil, and heavy fuel oil consumption, in m^3	OMH, INSTAT
Total energy consumption	TEC	Btu aggregation of electricity consumption and petroleum consumption, in MMBtu	Calculated
Energy imports	EMG	Volume of imported energy: sum of imported petroleum and other fuel products, in kg	Douane Malagasy
World oil prices	WOP	Global price of Brent crude, in U.S. Dollars per Barrel	FRED
Energy consumer prices	$ECPI$	Energy consumer price index, 2016 = 100	INSTAT
Energy import prices	$EMPI$	Energy imports price index (energy imports in value terms divided by energy imports in volume terms ×100), 2007 = 100	Douane Malagasy
Energy prices	EPI	Energy price index (PCA index)	Calculated

Furthermore, Bartlett's test of sphericity confirmed that the variables are correlated ($\chi^2(3) = 75.466$, p-value $= 0.000 < 0.05$), hence suggesting a sufficient level of correlation for the PCA technique.

Table 2: Results of the KMO and Barlett tests

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.568
Bartlett's test of sphericity	Approx. chi-square	75.466^{***}
	df	3

Note: *** denotes statistical significance at 1%.

The PCA results in Table 3 show that the first principal component explains the maximum variance (70.047%) in all the individual indicators, with an eigenvalue of 2.101. The remaining variance is captured by the second and third principal components, which explain 23.363% and 6.590% of the variance, respectively, with eigenvalues of 0.701 and 0.198. Following the Kaiser criterion, which recommends retaining only components with an eigenvalue above one (Kaiser, 1960), we select the first principal component to construct the composite energy price index, which we denote by EPI.

2.2 Econometric models

To examine the impact of economic growth on energy consumption, we develop three econometric models: Model A analyzes electricity consumption, Model B analyzes petroleum consumption, and Model C analyzes total energy consumption. Energy imports and energy prices are used as control variables for all three models. The models are specified in equations (2), (3) and (4) as follows:

$$\textbf{Model A}: \qquad ELC_t = \beta_0^A + \beta_1^A GDP_t + \beta_2^A EMG_t + \beta_3^A EPI_t + \varepsilon_t^A, \tag{2}$$

Table 3: Principal Components Analysis

Eigenvalues (sum = 3, average = 1)			
Number	Value	Proportion (in %)	Cumulative proportion (in %)
1	2.101	70.047	70.047
2	0.701	23.363	93.410
3	0.198	6.590	100.000
Eigenvectors (loadings)			
Variable	PC 1	PC 2	PC 3
WOP	0.642	−0.183	−0.744
ECPI	0.478	0.855	0.201
EMPI	0.599	−0.485	0.637
Ordinary correlations			
	WOP	*ECPI*	*EMPI*
WOP	1		
ECPI	0.505^{***}	1	
EMPI	0.778^{***}	0.336^{***}	1

Note: *** denotes statistical significance at 1%.

$$\textbf{Model B}: \quad PEC_t = \beta_0^B + \beta_1^B GDP_t + \beta_2^B EMG_t + \beta_3^B EPI_t + \varepsilon_t^B, \tag{3}$$
$$\textbf{Model C}: \quad TEC_t = \beta_0^C + \beta_1^C GDP_t + \beta_2^C EMG_t + \beta_3^C EPI_t + \varepsilon_t^C, \tag{4}$$

where the variables are defined in Table 1, the β_0^j's are the constant terms, the β_i^j's are the long-run coefficients, and ε_t^j are the usual white noise errors.

2.3 Unit root test

To determine the order of integration for the series in our model, we employ the Ng-Perron unit root test proposed by Ng and Perron (2001). This test is particularly advantageous as it exhibits strong size and explanatory power, even in small data samples like the one at hand. As a robustness check, we also apply the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) unit root test (Kwiatkowski et al., 1992) and the Dickey-Fuller Generalized Least Squares (DF-GLS) unit root test (Elliott et al., 1996).

The results of the Ng-Perron, KPSS, and DF-GLS unit root tests for both "intercept" and "trend and intercept" specifications are reported in Table 4. The unit root test results indicate that the inclusion of an intercept term yields stationarity only after first differencing for all series. Furthermore, when both trend and intercept are incorporated, the three tests agree that the series corresponding to *ELC*, *EMG*, *ECPI*, and *EMPI* exhibit non-stationarity at the level but achieve stationarity upon first differencing. In contrast, the *TEC*, *PEC*, and *GDP* series are found to be trend-stationary according to all three tests. Both the Ng-Perron and DF-GLS tests indicate that *WOP* and *EPI* are not stationary at the level, while the KPSS test concludes that these series are trend-stationary. However, it is clear that all series are stationary after first differencing. These findings collectively suggest that all the series under investigation are integrated of order one, i.e., I(1).

Note that the Ng-Perron, KPSS and DF-GLS unit root tests do not accommodate the structural break point arising in the series which may disproportionately lead to a null hypothesis rejection. We handle this issue by applying the Zivot-Andrews test for detecting the presence of endogenous structural breaks (Zivot and Andrews, 1992). To test for a unit root against the alternative of trend stationarity process with a structural break, Zivot and Andrews (1992) proceeded with three econometric models: Model ($\boldsymbol{a}$) allows a

Table 4: Ng-Perron, KPSS and DF-GLS unit root tests results

Variable	**Ng-Perron**				**KPSS**	**DF-GLS**
	MZa	**MZt**	**MSB**	**MPT**		
			With intercept			
Level						
GDP	0.148	0.076	0.514	20.387	0.993^{***}	−0.130
ELC	1.389	1.514	1.090	87.852	1.008^{***}	1.093
PEC	−0.454	−0.248	0.545	19.592	1.041^{***}	−0.354
TEC	−0.097	−0.057	0.594	23.719	0.989^{***}	−0.206
EMG	−1.270	−0.617	0.486	14.338	0.816^{***}	−1.422
EPI	−1.594	−0.522	0.328	9.793	0.740^{***}	−0.586
WOP	−4.181	−1.108	0.265	6.285	0.407^{*}	−1.213
ECPI	1.104	1.119	1.014	72.900	0.941^{***}	0.771
EMPI	−6.825	−1.600	0.234	4.417	0.423^{*}	−1.533
First difference						
ΔGDP	-26.114^{***}	−3.599	0.138	0.984	0.067	-11.832^{***}
ΔELC	-30.728^{***}	−3.918	0.127	0.804	0.016	-7.293^{***}
ΔPEC	-32.641^{***}	−4.004	0.123	0.860	0.057	-7.208^{***}
ΔTEC	-30.985^{***}	−3.893	0.126	0.922	0.074	-7.830^{***}
ΔEMG	-24.703^{***}	−3.425	0.139	1.287	0.099	-4.797^{***}
ΔEPI	-20.490^{***}	−3.195	0.156	1.218	0.097	-4.588^{***}
ΔWOP	-30.231^{***}	−3.882	0.128	0.829	0.082	-6.682^{***}
$\Delta ECPI$	-30.726^{***}	−3.919	0.128	0.799	0.149	-7.124^{***}
$\Delta EMPI$	-25.558^{***}	−3.550	0.139	1.041	0.202	-12.120^{***}
			With trend and intercept			
Level						
GDP	-26.980^{***}	−3.669	0.136	3.402	0.104	-5.285^{***}
ELC	−7.771	−1.971	0.254	11.726	0.147^{**}	−2.376
PEC	-18.071^{**}	−2.970	0.164	5.262	0.071	-3.515^{**}
TEC	-17.728^{**}	−2.937	0.166	5.383	0.068	-3.510^{**}
EMG	−11.054	−2.304	0.208	8.480	0.187^{**}	−2.676
EPI	−12.907	−2.492	0.193	7.334	0.094	−2.802
WOP	−9.982	−2.176	0.218	9.391	0.094	−2.371
ECPI	−4.979	−1.557	0.313	18.198	0.231^{***}	−1.695
EMPI	−10.836	−2.272	0.210	8.689	0.136^{*}	−2.379
First difference						
ΔGDP	-25.412^{***}	−3.562	0.140	3.600	0.060	-12.275^{***}
ΔELC	-29.638^{***}	−3.841	0.130	3.126	0.013	-9.536^{***}
ΔPEC	-32.921^{***}	−4.008	0.122	3.045	0.050	-7.743^{***}
ΔTEC	-31.000^{***}	−3.913	0.126	3.077	0.053	-7.753^{***}
ΔEMG	-30.466^{***}	−3.898	0.128	3.019	0.034	-7.398^{***}
ΔEPI	-30.330^{***}	−3.880	0.128	3.084	0.089	-9.005^{***}
ΔWOP	-30.589^{***}	−3.911	0.128	2.979	0.077	-6.984^{***}
$\Delta ECPI$	-30.905^{***}	−3.930	0.127	2.957	0.052	-7.394^{***}
$\Delta EMPI$	-24.301^{***}	−3.452	0.142	3.950	0.018	-12.795^{***}

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. The Ng-Perron and DF-GLS unit root tests apply the Schwarz Bayesian Information Criterion (SBIC) to automatically determine the optimal lag length. The bandwidth for the KPSS test is automatically selected through the bandwidth selection procedure proposed by Newey and West (1994). The null hypothesis of the Ng-Perron and DF-GLS unit root tests is that the series is non-stationary, while the null hypothesis of the KPSS test is that the series is stationary.

one-time change in the level of the series; Model (*b*) allows for a one-time change in the slope of the trend function and Model (*c*) combines changes in the level and the slope of the trend function of the series. The equations corresponding to these models are described in (5), (6) and (7) as follows:

$$\textbf{Model } (\boldsymbol{a}): \quad \Delta y_t = \gamma^{(\boldsymbol{a})} + \alpha^{(\boldsymbol{a})} y_{t-1} + \beta^{(\boldsymbol{a})} t + \delta^{(\boldsymbol{a})} DU_t + \sum_{j=1}^{p} \phi_j^{(\boldsymbol{a})} \Delta y_{t-j} + \varepsilon_t^{(\boldsymbol{a})}, \tag{5}$$

$$\textbf{Model } (\boldsymbol{b}): \quad \Delta y_t = \gamma^{(\boldsymbol{b})} + \alpha^{(\boldsymbol{b})} y_{t-1} + \beta^{(\boldsymbol{b})} t + \theta^{(\boldsymbol{b})} DT_t + \sum_{j=1}^{p} \phi_j^{(\boldsymbol{b})} \Delta y_{t-j} + \varepsilon_t^{(\boldsymbol{b})}, \tag{6}$$

$$\textbf{Model } (\boldsymbol{c}): \quad \Delta y_t = \gamma^{(\boldsymbol{c})} + \alpha^{(\boldsymbol{c})} y_{t-1} + \beta^{(\boldsymbol{c})} t + \delta^{(\boldsymbol{c})} DU_t + \theta^{(\boldsymbol{c})} DT_t + \sum_{j=1}^{p} \phi_j^{(\boldsymbol{c})} \Delta y_{t-j} + \varepsilon_t^{(\boldsymbol{c})}, \tag{7}$$

where term DU_t is a sustained dummy variable that captures a mean shift in the intercept occurring at time τ_B, and DT_t denotes shift in the trend occurring at time τ_B. These dummy variables are defined as

$$DU_t = \begin{cases} 1 & if\, t > \tau_B, \\ 0 & otherwise, \end{cases} \text{ and } DT_t = \begin{cases} t - T_B & if\, t > \tau_B, \\ 0 & otherwise. \end{cases}$$

The null hypothesis in Zivot and Andrews (1992) test, corresponding to $\alpha^{(\boldsymbol{i})} = 0$, is that the variable under investigation contains a unit root with a drift that excludes any structural break. The alternative hypothesis $\alpha^{(\boldsymbol{i})} < 0$ implies that the series is a trend-stationary process in which a one-time break in the trend variable occurs at an unknown point in time. The Zivot-Andrews test regards every point as a potential break-date and runs a regression for every possible break-date sequentially. From amongst all possible break-points, the procedure selects as its choice of break-date the date which minimizes the one-sided t-statistic for testing the null hypothesis.

Table 5: Zivot-Andrews unit root test results

Variable	**Level**			**First difference**		
	(*a*) Intercept	**(*b*) Trend**	**(*c*) Trend and intercept**	**(*a*) Intercept**	**(*b*) Trend**	**(*c*) Trend and intercept**
ELC	−3.673	-6.831^{***}	−4.277	-6.836^{***}	-6.455^{***}	-6.816^{***}
	(2010Q2)	(2010Q4)	(2010Q2)	(2011Q2)	(2018Q2)	(2011Q1)
PEC	−4.702	−3.984	-5.76^{***}	-7.635^{***}	-7.555^{***}	-7.635^{***}
	(2020Q1)	(2017Q4)	(2020Q2)	(2019Q4)	(2011Q3)	(2019Q4)
TEC	−4.674	−3.983	-5.64^{***}	-7.769^{***}	-7.668^{***}	-7.769^{***}
	(2020Q1)	(2018Q3)	(2020Q2)	(2019Q4)	(2011Q3)	(2019Q4)
GDP	−4.307	−3.955	−4.456	-6.284^{***}	-5.732^{***}	-8.410^{***}
	(2016Q3)	(2010Q4)	(2020Q2)	(2020Q2)	(2017Q1)	(2020Q2)
EMG	−4.239	−3.620	−4.187	-9.927^{***}	-9.956^{***}	-10.263^{***}
	(2011Q4)	(2013Q4)	(2011Q4)	(2010Q3)	(2011Q1)	(2013Q1)
EPI	−4.649	−3.617	−4.513	-6.199^{***}	-5.917^{***}	-6.258^{***}
	(2014Q3)	(2020Q3)	(2014Q3)	(2012Q2)	(2020Q2)	(2019Q3)
WOP	−4.477	−3.174	−4.24	-7.228^{***}	-7.128^{***}	-5.429^{***}
	(2014Q4)	(2020Q3)	(2014Q4)	(2016Q2)	(2015Q2)	(2013Q1)
ECPI	−4.515	−3.392	-6.824^{***}	-8.135^{***}	-7.476^{***}	-8.453^{***}
	(2016Q1)	(2014Q3)	(2016Q1)	(2016Q1)	(2020Q2)	(2016Q1)
EMPI	−4.299	−3.764	−4.616	-6.212^{***}	-5.848^{***}	-6.154^{***}
	(2014Q3)	(2017Q2)	(2014Q3)	(2012Q2)	(2020Q2)	(2012Q4)

Note: *** denotes statistical significance at 1%. (.) reports the break date.

The results of the Zivot-Andrews unit root test are presented in Table 5. The outcomes suggest that the null hypothesis of a unit root cannot be rejected for all series in levels, with a few notable exceptions. Specifically, *ELC* is found to be a stationary process with a break in the intercept occurring in 2010Q4. Furthermore, *PEC*, *TEC*, and *ECPI* are found to exhibit trend stationarity with breaks in the intercept and the slope of the trend function, occurring specifically in 2020Q2 for *TEC* and *PEC*, and in 2016Q1 for *ECPI*. Importantly, all series become stationary after taking the first difference. Consequently, we conclude that all the series are integrated of order one, I(1).

2.4 Bayer-Hanck cointegration test

To ascertain the existence of a long-run association among the variables, we use the cointegration test suggested by Bayer and Hanck (2012). This cointegration test combines the Engle and Granger (1987), Johansen (1991), Banerjee et al. (2001) and Boswijk (1994) non-cointegration tests to obtain uniform and reliable cointegration results. Bayer and Hanck (2012) followed Fisher formula to combine the computed significance level, i.e., the p-values, of the individual cointegration to strengthen the test:

$$\mathrm{EG-Jo} = -2\big[\log(p_{EG}) + \log(p_{Jo})\big],$$
$$\mathrm{EG-Jo-Ba-Bo} = -2\big[\log(p_{EG}) + \log(p_{Jo}) + \log(p_{Ba}) + \log(p_{Bo})\big],$$

where p_{EG}, p_{Jo}, p_{Ba} and p_{Bo} represent the probability values of Engle and Granger (1987), Johansen (1991), Banerjee et al. (2001) and Boswijk (1994), respectively. If the computed Fisher statistics exceed the critical values, then the null hypothesis of non-cointegration will be rejected.

For each model, the F-statistics reported in Table 6 are higher than the critical values at a 5%, or better, significance level. Therefore, we reject the null-hypothesis of non-cointegration and conclude the existence of a long-term relationship between energy consumption and the key economic variables.

Table 6: Bayer-Hanck cointegration test results

Model specification	**Fisher statistics**		**Cointegration decision**
	EG – Jo	EG – Jo – Ba – Bo	
$F_{ELC}(ELC_t \mid GDP_t, EMG_t, EPI_t)$	14.965**	26.270**	yes
$F_{PEC}(PEC_t \mid GDP_t, EMG_t, EPI_t)$	32.447***	49.768***	yes
$F_{TEC}(TEC_t \mid GDP_t, EMG_t, EPI_t)$	29.910***	40.702***	yes
Critical values for Fisher statistics			
1%	16.259	31.169	
5%	10.637	20.486	
10%	8.363	16.097	

Note: *** and ** denote statistical significance at 1% and 5%, respectively.

2.5 Long-run elasticities estimation

Since the cointegration between the variables is confirmed, we employ the Fully Modified Ordinary Least Squares (FMOLS) method proposed by Phillips and Hansen (1990), the Dynamic Ordinary Least Squares (DOLS) method proposed by Saikkonen (1992) and Stock and Watson (1993), and the Canonical Cointegrating Regression (CCR) method proposed by Park (1992) to assess the long-run elasticities between the dependent and independent variables. The FMOLS approach accounts for the endogeneity of regressors and corrects for the serial correlation that is typically present in long-run estimations when the data is non-stationary. Additionally, the DOLS technique addresses endogeneity problems and provides unbiased cointegrating coefficient estimates by including future and past values of the differenced explanatory variables as additional regressors. Furthermore, the CCR method is concerned with the cointegration of a variable in its specific canonical class regression. Montalvo (1995) showed that the CCR estimator exhibits smaller bias than the OLS and FMOLS estimators, and the DOLS estimator performs systematically better than the CCR estimator.

The empirical results presented in Table 7 are consistent across various models and estimation methods. We find that economic growth, energy imports, and energy prices each have a positive and statistically significant impact on energy consumption in Madagascar, indicating that these factors are important drivers of the country's energy demand.

Starting with Model A, the estimates show that a 1% increase in real GDP is associated with a substantial rise in electricity consumption, ranging from 1.36% (FMOLS) to 1.368% (DOLS) and 1.390% (CCR). These results suggest that electricity consumption is elastic to changes in real GDP, and underscore the strong link between economic growth and the demand for electricity. Our findings are in alignment with empirical studies conducted by Amarawickrama and Hunt (2008) for Sri Lanka, Amusa et al. (2009) for South Africa, Polemis and Dagoumas (2013) for Greece, Tang and Tan (2013) for Malaysia, Talbi (2012) and Talbi and Nguyen (2012) for Tunisia, Ridzuan et al. (2019) for Malaysia, and Murshed (2021) for Bangladesh. However, the elasticity we found is higher than the positive elasticity reported by De Vita et al. (2006) for Namibia, Alawin et al. (2016) for Jordan, Hasanov et al. (2016) for Azerbaijan, and Mohapatra and Giri (2020) for India.

Furthermore, the positive impact of a 1% increase in energy imports on electricity consumption, ranging from 0.077% (FMOLS) to 0.084% (DOLS) and 0.077% (CCR), can be attributed to JIRAMA (Jiro sy Rano Malagasy, Madagascar's national water and electricity company)'s heavy reliance on fossil fuels for electricity generation (MEH, 2019). This finding highlights the need for Madagascar to diversify its electricity generation mix to reduce its dependence on imported and polluting energy sources (Praene et al., 2017; Surroop and Raghoo, 2018; Kabeyi and Olanrewaju, 2022).

Turning to Model B, the estimates indicate that a 1% increase in real GDP is associated with a positive and significant rise in petroleum consumption, ranging from 0.965% (FMOLS) to 0.976% (DOLS) and 0.961% (CCR), underscoring the strong link between economic growth and the demand for fossil-based energy sources. While the sign of the elasticity is consistent with several prior empirical studies, the magnitude obtained in this analysis appears relatively low compared to the higher elasticities reported by De Vita et al. (2006) for Namibia, Fei and Rasiah (2014) for Ecuador and Norway, Pinzón (2016) for Ecuador, Raghoo and Surroop (2020) for Mauritius (considering gasoline and fuel oil), and Flavien et al. (2020) for Cameroon households (considering kerosene). Conversely, the elasticity value found here is larger than those reported by Abdel-Khalek (1988) for Egypt, Mitchel (2006) for Barbados, Iwayemi et al. (2010) for Nigeria, Talbi (2012) and Talbi and Nguyen (2012) for Tunisia, Fei and Rasiah (2014) for South Africa and Canada, Narayan et al. (2019) for Indian states, Sina (2019) for Iran, Flavien et al. (2020) for Cameroon households (considering LPG), and Abdullahi and Sani (2021) for Nigeria. In Madagascar, key economic activities that drive petroleum demand include the transportation sector and the mining industry, both of which are vital contributors to the country's overall economic growth (OMH, 2023).

Additionally, our analysis reveals a positive correlation between energy imports and petroleum consumption in Madagascar. A 1% increase in energy imports is associated with a rise in petroleum consumption ranging from 0.197% (FMOLS) to 0.209% (DOLS) and 0.202% (CCR). This suggests that Madagascar's reliance on imported energy sources, primarily fossil fuels, contributes to higher overall energy use. This dependence raises concerns about energy security and trade balances, as highlighted by Subtil (2021). Mitchel (2006) found a similar result for Barbados, with an elasticity approaching 0.14, using a different proxy –the ratio of fuel imports to nominal GDP– to capture energy intensity. In contrast, Murshed (2021) found a significantly higher elasticity of energy imports to energy consumption in Bangladesh (1.23), leading him to conclude that energy imports have served as a long-term strategy for mitigating traditional energy crises in the country.

Finally, Model C reveals a significant positive relationship between economic growth and total energy consumption in Madagascar. A 1% increase in real GDP is associated with a substantial increase in total energy cosnumption, ranging from 1.058% (FMOLS) to 1.111% (DOLS) and 1.060% (CCR). In contrast to Narayan et al. (2010), who reported a negative and statistically insignificant elasticity for Madagascar, the average elasticity in this study is slightly lower than the 1.329 value reported by Seale Jr et al. (1991) for the country, and the sign and magnitude are consistent with findings from other studies. For example, Olatubi and Zhang (2003) found similar results for Southern States, De Vita et al. (2006) for Namibia, Ishida (2015) for Japan, Keho (2016) for the Congo Republic, Hassan (2018) for the Association of Southeast Asian Nations-5, ASEAN-5 (Indonesia, Malaysia, Singapore, Thailand and the Philippines), Wang et al. (2019) for a group of high income countries, Murshed (2021) for Bangladesh, and Oryani et al. (2022) for Iran. Several other studies have also reported positive elasticities below unity, including Al-Azzam and Hawdon (1999) for Jordan, Weixian (2002) for China, Sadorsky (2010) for a group of 22 emerging countries, Talbi (2012) and Talbi and Nguyen (2012) for Tunisia, Chang (2015) for a group of 53 countries, Komal and Abbas (2015) for Pakistan, Keho (2016) for 12 Sub-Saharan African (Cameroon, Democratic Republic of the Congo, Cote d'Ivoire, Gabon, Ghana, Kenya, Nigeria, Senegal, South Africa and Togo) Mukhtarov et al. (2020) for Kazakhstan, Li and Solaymani (2021) for Malaysia, and Shahzad (2021) for ten newly industrialized countries (Brazil, China, India, Indonesia, Mexico, Malaysia, Philippines, South Africa, Thailand, and Turkey). These findings underscore the strong correlation between economic growth and increasing energy demand, emphasizing the need for policymakers to account for the energy implications of economic activities and to develop strategies for decoupling economic development from rising energy consumption, thereby supporting more sustainable pathways (Guo et al., 2021; Chen et al., 2024).

The positive correlation between energy imports and total energy consumption in Madagascar is further highlighted by our results, which show that a 1% rise in energy imports leads to an increase in total energy consumption of 0.174% (FMOLS), 0.167% (DOLS), and 0.177% (CCR). This reinforces the significant dependence on imported energy, primarily for industries, transportation, households, construction projects, and electricity generation (Sharma et al., 2019).

The analysis across all three models reveals a consistent pattern of a small but positive relationship between changes in the energy prices and consumption, suggest that higher prices lead to increased energy use. Specifically, a 1% change in the energy price index is associated with an increase in energy consumption of 0.016% to 0.017% across the three estimators for electricity consumption, 0.022% across all three estimators for petroleum consumption, and 0.023% (FMOLS), 0.026% (DOLS), and 0.022% (CCR) for total energy consumption. Our results are consistent with those of Amusa et al. (2009) who reported that electricity prices have a positive and insignificant effect on aggregate electricity demand in South Africa. These results are also in line with Sadorsky's (2010) findings for a group of 22 emerging countries. Sadorsky (2010) attributed the positive estimated coefficient on the price variable to either a poor choice of the author's energy prices proxy (consumer price index), or the capacity of fast-growing countries to increase their demand for energy even when prices are rising over short periods of time. Fei and Rasiah (2014) found a positive elasticity for Norway, attributing it to the country's low reliance on fossil fuel-based energy sources. Chang (2015) observed a positive relationship between energy prices and energy consumption across 58 countries, but the coefficient was small and statistically insignificant. Similarly, Pinzón (2016) reported a positive relationship in Ecuador, but again, it was not statistically significant. Our findings also align with previous research by Hassan (2018) who found a positive correlation between energy prices (specifically world prices) and energy demand in the ASEAN-5, particularly for aggregate, natural gas, and solid fuels demand. Analogously, Wang et al. (2019) conducted a comprehensive study across 186 countries and discovered similar patterns. Their study revealed that the effects of energy price changes on energy consumption were particularly pronounced in high-income nations, where the impact of price changes on energy demand was more significant. These findings, however, contradict the conventional expectation that higher energy prices would lead to reduced consumption.

While previous research by Seale Jr et al. (1991) for Madagascar reported negative elasticity coefficients of energy prices to energy consumption, ranging from -0.923 to -0.970, our results suggest a different dynamic. This divergence is also evident in empirical studies by Abdel-Khalek (1988) for Egypt, Al-Azzam and Hawdon (1999) for Jordan, Weixian (2002) and Yuan et al. (2010) for China, Olatubi and Zhang (2003) for Southern States, De Vita et al. (2006) for Namibia, Mitchel (2006) for Barbados, Iwayemi et al. (2010) for Nigeria, Talbi (2012) and Talbi and Nguyen (2012) for Tunisia, Tang and Tan (2013) and Li and Solaymani (2021) for Malaysia, Polemis and Dagoumas (2013) for Greece, Fei and Rasiah (2014) for

Ecuador, South Africa, and Canada, Komal and Abbas (2015) for Pakistan, Ishida (2015) for Japan, Alawin et al. (2016) for Jordan, Hasanov et al. (2016) for Azerbaijan, Sina (2019) for Iran, Mohapatra and Giri (2020) for India, Mukhtarov et al. (2020) for Kazakhstan, Abdullahi and Sani (2021) for Nigeria, Murshed (2021) for Bangladesh, Shahzad (2021) for 10 newly industries countries (Brazil, China, India, Indonesia, Mexico, Malaysia, Philippines, South Africa, Thailand, and Turkey), and Oryani et al. (2022) for Iran.

Several other factors may be contributing to the positive relationship between energy prices and energy consumption in Madagascar. First, our energy price index may not adequately reflect the complexities of Madagascar's energy pricing system, particularly the subsidies applied to oil prices (CREAM, 2019). This potential bias could be contributing to a dampening of consumer price sensitivity, potentially leading to overconsumption of energy. Income effects or technological changes may also be offsetting the demand-reducing impact of price increases, leading to this unexpected positive relationship. As energy prices increase, some consumers may slightly reduce their energy consumption, while others may absorb the higher costs due to their higher income and better access to credit (Byaro and Mmbaga, 2022). Moreover, the country's economy is heavily reliant on energy-intensive industries such as mining and manufacturing, which may be less responsive to price changes due to their high energy demands (Adom and Amuakwa-Mensah, 2016). Additionally, the mix of products within an industry can shift towards more energy-intensive goods, leading to a small increase in overall energy demand. As a result, energy prices may have a small but positive influence on energy consumption, particularly in urban areas where economic growth and industrial activity are driving up energy demand (Château, 2022). Besides, the country's energy infrastructure are not optimized for energy efficiency, leading to higher energy consumption even at higher prices (Batinge et al., 2019; Baskaran and Coste, 2024). Rapid urbanization may also be contributing to increased energy consumption as people move to cities and adopt more energy-intensive lifestyles (Ali, 2021). Finally, the limited availability and accessibility of alternative energy sources, such as renewable energy, may make it difficult for consumers to switch away from conventional energy sources, even at higher prices (Yang and Yang, 2018; Kabel and Bassim, 2020; Ramaharo and Razanajatovo, 2024).

Note that, for each model, the Engle-Granger residual-based tests are also reported to ascertain the existence of a cointegrating relationship between the concerned energy consumption and its corresponding dependent variables. Both the Engle-Granger tau-statistic and normalized autocorrelation coefficient (z-statistic) are greater than the critical values reported by MacKinnon (2010), meaning that the null hypothesis of no cointegration can be rejected in favor of the alternative hypothesis of cointegration. Moreover, the adjusted R-squared values for each of the three models, which range from 0.926 to 0.970 across the three estimators (FMOLS, DOLS, and CCR), indicate a satisfactory fit, suggesting that the models are able to capture a significant portion of the variability in energy consumption. Each residuals are also checked to be normally distributed, as confirmed by the Jarque-Bera test, with probabilities all larger than 0.10.

2.6 Robustness and sensitivity tests

To ensure the robustness of our estimates, we employ the Robust Least Squares (RLS) method and select the M-estimation (Huber, 1973; Pitselis, 2013). The advantage of the RLS method is that it can mitigate the outlier effect of the explanatory variables and provide efficient parameter estimation even in the presence of influential data points. Additionally, we conduct a sensitivity analysis by substituting the energy price index with individual energy prices used in its construction. This two-pronged approach allows us to achieve two key objectives. Firstly, we verify the positive sign of the energy price coefficient and examined whether the coefficients associated with economic growth and energy imports vary significantly in response to these changes. Secondly, we validate the stability and consistency of the key relationships identified in the initial analysis, even when modifying the specification of the energy price variable. By doing so, we are able to strengthen the credibility and reliability of our findings, addressing potential concerns about the sensitivity of the results to the choice of energy price measure.

As shown in Table 8, the RLS estimation results closely match those from DOLS, CCR, and FMOLS approaches. Although coefficient magnitudes differ slightly, the overall findings are consistent with earlier results. Importantly, all variables maintain their expected signs and are highly statistically significant.

Table 7: Long-run estimation results

	Coefficient (Std. Error)		
	FMOLS	**DOLS**	**CCR**
Dependent variable: ELC_t			
GDP_t	1.360 (0.094)***	1.368 (0.113)***	1.390 (0.109)***
EMG_t	0.077 (0.030)**	0.084 (0.035)**	0.077 (0.036)**
EPI_t	0.017 (0.006)***	0.016 (0.007)**	0.016 (0.007)**
Constant	−6.901 (0.623)***	−7.053 (0.728)***	−7.149 (0.686)***
R -squared	0.938	0.961	0.935
Adjusted R-squared	0.928	0.950	0.926
S.E. of regression	0.054	0.044	0.054
Long-run variance	0.002	0.002	0.002
Jarque-Bera [Prob.]	1.061 [0.588]	2.733 [0.255]	0.955 [0.62]
Engle-Granger tau-statistic	−7.991***		
Engle-Granger z-statistic	−63.067***		
Dependent variable: PEC_t			
GDP_t	0.965 (0.101)***	0.976 (0.111)***	0.961 (0.113)***
EMG_t	0.197 (0.030)***	0.209 (0.035)***	0.202 (0.035)***
EPI_t	0.023 (0.006)***	0.022 (0.007)***	0.022 (0.007)***
Constant	1.704 (0.676)**	1.459 (0.713)**	1.676 (0.732)**
R-squared	0.943	0.969	0.943
Adjusted R-squared	0.938	0.962	0.938
S.E. of regression	0.050	0.039	0.050
Long-run variance	0.003	0.002	0.003
Jarque-Bera [Prob.]	2.418 [0.299]	1.135 [0.567]	2.559 [0.278]
Engle-Granger tau-statistic	−5.892***		
Engle-Granger z-statistic	−46.745***		
Dependent variable: TEC_t			
GDP_t	1.058 (0.093)***	1.111 (0.111)***	1.060 (0.105)***
EMG_t	0.174 (0.028)***	0.167 (0.035)***	0.177 (0.033)***
EPI_t	0.023 (0.006)***	0.026 (0.008)***	0.022 (0.006)***
Constant	−2.014 (0.626)***	−2.366 (0.706)***	−2.065 (0.676)***
R-squared	0.949	0.977	0.949
Adjusted R-squared	0.945	0.97	0.944
S.E. of regression	0.048	0.035	0.048
Long-run variance	0.002	0.002	0.002
Jarque-Bera [Prob.]	2.272 [0.321]	0.191 [0.909]	2.278 [0.320]
Engle-Granger tau-statistic	−6.131***		
Engle-Granger z-statistic	−48.719***		

Note: *** and ** denote statistical significance at 1% and 5%, respectively. Time dummies to account for level shifts or outliers are not displayed in the table. Superscripts *** following the Engle-Granger tau-statistic and z-statistic indicate statistical significance at 1% level based on MacKinnon's (2010) critical values against the null hypothesis that series are not cointegrated.

Table 8: Robust Least Squares estimation results

	Coefficient (Std. Error)			
	1.	**2.**	**3.**	**4.**
Dependent variable: ELC_t				
GDP_t	1.293 (0.011)***	1.378 (0.011)***	1.287 (0.013)***	1.279 (0.011)***
EMG_t	0.043 (0.003)***	0.050 (0.004)***	0.020 (0.005)***	0.088 (0.003)***
EPI_t	0.023 (0.001)***	-	-	-
WOP_t	-	0.075 (0.003)***	-	-
$ECPI_t$	-	-	0.159 (0.009)***	-
$EMPI_t$	-	-	-	0.100 (0.003)***
Constant	−5.908 (0.071)***	−7.093 (0.066)***	−6.387 (0.081)***	−6.826 (0.062)***
R-squared	0.755	0.783	0.849	0.772
Adjusted R-squared	0.720	0.751	0.827	0.739
R_w-squared	0.958	0.948	0.940	0.955
Adjust R_w-squared	0.958	0.948	0.940	0.955
Jarque-Bera [Prob.]	1.823 [0.402]	0.134 [0.935]	0.286 [0.867]	2.084 [0.353]
Dependent variable: PEC_t				
GDP_t	0.888 (0.009)***	0.977 (0.009)***	0.929 (0.012)***	0.890 (0.01)***
EMG_t	0.180 (0.003)***	0.179 (0.003)***	0.194 (0.004)***	0.222 (0.003)***
EPI_t	0.026 (0.001)***	-	-	-
WOP_t	-	0.103 (0.003)***	-	-
$ECPI_t$	-	-	0.076 (0.008)***	-
$EMPI_t$	-	-	-	0.114 (0.003)***
Constant	2.567 (0.062)***	1.313 (0.056)***	1.658 (0.077)***	1.475 (0.056)***
R-squared	0.862	0.874	0.848	0.881
Adjusted R-squared	0.842	0.856	0.826	0.864
R_w-squared	0.966	0.964	0.952	0.963
Adjust R_w-squared	0.966	0.964	0.952	0.963
Jarque-Bera [Prob.]	1.394 [0.498]	0.871 [0.647]	1.250 [0.535]	1.976 [0.372]
Dependent variable: TEC_t				
GDP_t	1.015 (0.009)***	1.113 (0.009)***	1.045 (0.012)***	1.015 (0.009)***
EMG_t	0.143 (0.003)***	0.144 (0.003)***	0.153 (0.004)***	0.189 (0.003)***
EPI_t	0.029 (0.001)***	-	-	-
WOP_t	-	0.107 (0.003)***	-	-
$ECPI_t$	-	-	0.102 (0.007)***	-
$EMPI_t$	-	-	-	0.125 (0.003)***
Constant	−1.26 (0.058)***	−2.643 (0.052)***	−2.159 (0.074)***	−2.439 (0.053)***
R-squared	0.875	0.875	0.846	0.869
Adjusted R-squared	0.857	0.857	0.824	0.850
R_w-squared	0.969	0.966	0.955	0.967
Adjust R_w-squared	0.969	0.966	0.955	0.967
Jarque-Bera [Prob.]	0.970 [0.616]	0.233 [0.890]	0.438 [0.804]	1.276 [0.528]

Note: *** denotes statistical significance at 1%, respectively. R_w-squared are calculated using Renaud and Victoria-Feser (2010) robust estimates.

Furthermore, the coefficients for economic growth and energy imports exhibit robustness to different energy price measures. We conclude that the effects of world oil prices and energy imports in the models are similar to those of the subsidized prices, which are captured by the energy consumer price index. This suggests that the dynamics between economic growth, energy imports, and energy consumption remain unchanged in response to exogenous prices, implying that the subsidy has effectively insulated energy consumption from external price shocks.

2.7 Granger causality test

The literature on the energy-growth nexus identifies four primary hypotheses that characterize the causal relationship between energy consumption and economic activity (Ozturk, 2010). The "growth hypothesis" posits a unidirectional causality running from energy consumption to economic growth, suggesting that increases in energy use directly and indirectly drive economic growth by complementing labor and capital inputs, and, therefore, inadequate provision of energy limits economic growth. Conversely, the "conservation hypothesis" proposes a unidirectional causality from economic growth to energy consumption, implying that energy conservation policies may be implemented without adversely impacting growth. The "feedback hypothesis" describes a bidirectional relationship between energy and economic growth, implying a complementary relationship. This means that policies promoting efficient energy use can stimulate economic growth, and vice versa, as an increase in one fuels growth in the other. Finally, the "neutrality hypothesis" assumes no significant causal relationship between energy consumption and economic growth, indicating that adjustments in energy use would have little to no impact on economic performance. In this paper, we will examine the causal relationship in both the time and frequency domains (Ghodsi and Huang, 2015; Ahmed and Azam, 2016; Sica and Sentürk, 2016; Gorus and Aydin, 2019; Yildiz, 2022; Akça, 2023; Saliminezhad and Bahramian, 2023).

2.7.1 Toda-Yamamoto Granger non-causality test

We first apply the Toda-Yamamoto Granger non-causality test to examine the causal relationships among the variables under consideration. This method is advantageous as it can be applied regardless of the cointegration status and order of integration of the series, thereby avoiding the uncertainties associated with pre-testing for cointegration and unit roots (Toda and Yamamoto, 1995; Dolado and Lütkepohl, 1996). The Toda-Yamamoto approach involves estimating a $(p + d_{max})$th-order level Vector Autoregressive (VAR) model, where p is the appropriate lag length of the VAR model, which is determined using Information Criteria, and d_{max} is the maximum order of integration of the variables. The VAR representation of the total energy consumption model can be expressed as follows:

$$\begin{pmatrix} TEC_t \\ GDP_t \\ EMG_t \\ EPI_t \end{pmatrix} = \boldsymbol{A}_0 + \sum_{j=1}^{p} \boldsymbol{A}_j \begin{pmatrix} TEC_{t-j} \\ GDP_{t-j} \\ EMG_{t-j} \\ EPI_{t-j} \end{pmatrix} + \sum_{j=p+1}^{p+d_{max}} \boldsymbol{A}_j \begin{pmatrix} TEC_{t-j} \\ GDP_{t-j} \\ EMG_{t-j} \\ EPI_{t-j} \end{pmatrix} + \begin{pmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \\ \varepsilon_{3,t} \\ \varepsilon_{4,t} \end{pmatrix},$$

where $\mathbf{A}_0 = [\alpha_1^0, \alpha_2^0, \alpha_3^0, \alpha_4^0]^\intercal$ is a vector of constants, $\mathbf{A}_j = \left(\alpha_{i,\ell}^j\right)_{\substack{i=1,\dots,4 \\ \ell=1,\dots,4}}$, $j = 1, \dots, p, p+1, \dots, p + d_{max}$, is the matrix of coefficients of the VAR$(p + d_{max})$ model, and $\varepsilon_{i,t}$ are the serially uncorrelated random disturbance terms with zero mean. Equations for ELC_t and PEC_t can be constructed in the same fashion. The modified Wald (MWald) test is used to test the direction of causal relationship among the variables under study. The null hypothesis of non-causality: H_0: "the ℓ-th variable does not Granger-cause the i-th variable", is expressed as

$$H_0 : \alpha_{i\ell}^1 = \alpha_{i\ell}^2 = \cdots = \alpha_{i\ell}^p = 0,$$

i.e., the MWald test is carried out only on the coefficients of p lagged variables. For example, the null hypothesis $H_0 : \alpha_{12}^1 = \alpha_{12}^2 = \cdots = \alpha_{12}^p = 0$ indicates that GDP_t does not Granger-cause TEC_t. Based on the unit root test results in §2.3, we set $d_{max} = 1$.

Table 9: Toda-Yamamoto Granger non-causality test results

Dependent variables	Source of causality						
	ELC	*PEC*	*TEC*	*GDP*	*EMG*	*EPI*	All variables
Model A: $p = 5$, $d_{max} = 1$							
ELC	-			12.682**	19.838***	5.553	37.229***
GDP	2.546			-	3.019	5.876	19.423
EMG	3.038			7.096	-	3.404	15.074
EPI	2.806			14.174**	11.652**	-	25.388**
Model B: $p = 3$, $d_{max} = 1$							
PEC		-		3.674	4.049	1.468	9.231
GDP		3.865		-	0.969	4.647	28.066***
EMG		17.549***		6.930*	-	0.328	27.573***
EPI		8.568**		9.352**	5.646	-	14.898*
Model C: $p = 3$, $d_{max} = 1$							
TEC			-	4.084	3.180	1.249	8.929
GDP			5.210	-	0.865	4.087	27.171***
EMG			18.169***	8.149**	-	0.329	27.950***
EPI			9.306**	10.674**	5.872	-	16.434*

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. For each model, the Schwarz Bayesian Information Criterion (SBIC) is used to select the optimal lag order, which is gradually increased until the level VAR model is adequately specified.

The Toda-Yamamoto Granger non-causality test, presented in Table 9, reveals a long-run causal relationship running from economic growth to electricity consumption in Madagascar. No evidence of causality was found in the opposite direction, even at the 10% significance level. These findings align with previous research by Wolde-Rufael (2006) for Cameroon, Ghana, Nigeria, Senegal, Zambie and Zimbabwe, Shahbaz and Feridun (2011) and Balcilar et al. (2019) for Pakistan, Topalli and Alagöz (2014) for Turkey, and Sharaf (2016) for Egypt. However, they contradict the findings of Michieka (2015) who reported a neutral causality for Kenya, and Bekun and Agboola (2019) who uncovered a unidirectional causality running from electricity consumption to economic growth for Nigeria. The empirical study conducted by Andriamanga (2017) for Madagascar also concluded that electricity consumption Granger-causes economic growth at the 10% significance level, and the corresponding causality is only significant in that direction. Our finding supports the conservation hypothesis, indicating that energy conservation policies designed to reduce electricity consumption and waste may not have an adverse impact on economic growth. In practice, suggesting measures to reduce electricity consumption in Madagascar is not a viable option at this time. The country faces significant energy challenges and its aging infrastructure is inadequate to support rapid economic growth needed to address poverty and improve living standards (AfDB, 2017; Batinge et al., 2019; Baskaran and Coste, 2024; Rafitoson, 2017; Ida, 2024a). Furthermore, limited access to electricity persists in Madagascar, with only 36.1% of the population having access as of 2022 (World Bank, 2024). While reducing electricity consumption might seem like a solution, it is not yet advisable. Following the example of many African countries, Madagascar should focus on mitigating the detrimental consequences of electricity consumption without necessarily reducing overall consumption levels (Wolde-Rufael, 2005, 2006). The analysis reveals a unidirectional causality running from economic growth to energy prices, a finding that is supported by Murshed (2021) for Bangladesh. Our finding means that future energy prices in Madagascar can be predicted, to some extent, by monitoring economic activity.

The analysis further reveals two additional unidirectional causal relationships: a causality running from energy imports to electricity consumption, and another from energy imports to energy prices. The former suggests that reducing energy imports has an adverse effect on electricity consumption, which is particularly concerning for Madagascar, where electricity generation relies heavily on imported fuel oil (MEH, 2019). Historically, decreases in energy imports in Madagascar have led to electricity shortages and supply disruptions, highlighting the need for diversified energy sources and contingency planning to ensure a stable energy supply (Rafidiarisoa, 2017; Ida, 2024b). The latter causality implies that energy import policies can have direct implications for energy prices, which may impact energy importers and energy consumers. This has significant implications for policymakers, who should carefully consider the potential price effects of energy import policies. Higher energy prices can lead to increased production costs, higher inflation, and reduced competitiveness for energy-intensive industries. In addition, higher energy prices can also disproportionately affect low-income households, who may spend a larger proportion of their income on energy expenses (Naidoo and Loots, 2000; Rafitoson, 2017; Voninirina and Andriambelosoa, 2014). Therefore, policymakers should strive to design energy import policies that balance energy security concerns with the need to protect vulnerable populations and promote economic competitiveness (Müller et al., 2021).

On the contrary, for model B and C, it is also revealed that there is no causal relationship between economic growth and total energy consumption or petroleum consumption. The absence of causality between economic growth and total energy consumption is supported by the findings of Wolde-Rufael (2005) for Benin, Congo Republic, Kenya, Senegal, South Africa, Sudan, Tunisia, and Zimbabwe, Esso (2010) for Cameroon, Kenya, Nigeria and South Africa, Sharaf (2016) for Egypt, Kablamaci (2017) for 13 developing countries (Argentina, Bolivia, Cameroon, Colombia, Costa Rica, Dominican Republic, Indonesia, Jordan, Mauritius, Paraguay, Singapore, South Africa, Thailand. Benin, Senegal, Sudan and Zambia), Zerbo (2017) for Benin, Cote d'Ivoire, Congo Republic, Ghana, Senegal, South Africa and Togo, and Moftah and Dilek (2021) for Iran, Jordan, Saudi Arabia, Qatar, and Tunisia. However, these findings contrast with those of Zamani (2007) who found a unidirectional causality flowing from economic growth to total energy consumption, and bidirectional causality between economic growth and petroleum consumption in Iran. Furthermore, Esso (2010) uncovered bidirectional causality between economic growth and total energy consumption for Cote d'Ivoire, a finding echoed by Mukhtarov et al. (2020) for Kazakhstan, and Murshed (2021) for Bangladesh. While Ziramba (2014) established that petroleum consumption causes economic growth in South Africa, the opposite direction was reported by Lotfalipour et al. (2010) for Iran, Sharaf (2016) for Egypt, and Tamba (2021) for Cameroon. Notably, our findings differ from those of Andriamanga (2017) who uncovered bidirectional causality between economic growth and petroleum consumption in Madagascar, and Voninirina and Andriambelosoa (2014), who identified bidirectional causality between economic growth and total energy consumption. This discrepancy can be attributed to the data and model specifications used in each study. Our analysis, based on available quarterly energy data, focused on electricity and petroleum consumption, while Voninirina and Andriambelosoa (2014), for instance, utilized annual data, encompassing biomass and coal, which constitute the largest energy sources in Madagascar (MEH, 2019).

We also find that economic growth has a long-run causal effect on both energy imports and energy prices in Models B and C. Our findings contrast with those of Murshed et al. (2020), who found a causal relationship running from energy imports and energy prices to economic growth in Sri Lanka, and Hatemi-J and Irandoust (2005), who identified causality running from prices to economic growth. The results of our analysis highlight the predictive power of economic growth for energy imports and prices. This allows policymakers to anticipate changes in energy demand based on observed economic growth trends, enabling more informed energy planning and policy decisions. The analysis also identifies a unidirectional causal relationship running from both total energy consumption and petroleum consumption to energy imports. This suggests that increases in energy demand lead to higher energy imports, potentially increasing reliance on foreign energy sources and raising energy security concerns (Kim et al., 2024). Besides, the results show that total energy consumption and petroleum consumption have a unidirectional causal effect on energy prices, a finding that contrasts with Mukhtarov et al. (2020), who identified the opposite direction for total energy consumption in Kazakhstan. Our findings imply that increases in energy demand drive energy prices higher, highlighting the importance of energy demand management and the need to mitigate the impact of energy price shocks on the economy.

2.7.2 Breitung-Candelon frequency-domain causality test

To further investigate the causal effects of economic growth, energy imports, and energy prices on energy consumption at different frequencies, this study employs the frequency-domain causality test developed by Breitung and Candelon (2006). The Breitung-Candelon frequency-domain approach is preferred over the time-domain Granger causality test as it allows for the removal of seasonal fluctuations in the small sample data and enables the detection of causality between variables at low, medium, and high frequencies. The frequency-based decomposition of spectral density is founded on the early works of Granger (1969) and the framework proposed by Geweke (1982) and Hosoya (1991). This approach employs a Wald-type testing procedure for detecting causality at given frequencies. However, implementing frequency domain analysis has historically proven challenging due to non-linearities. Geweke (1982) proposed a Wald-test that imposes linear restrictions on the coefficient parameters. This test procedure was further elaborated by Breitung and Candelon (2006). They demonstrated that frequency-domain causality tests can be determined by imposing linear restrictions on the coefficients in a VAR model, allowing for testing informational linkages at any given frequency. Breitung and Candelon (2006) approach can be explained as follows.

Let $\boldsymbol{Y}_t = [x_t, y_t]^\intercal$ be a covariance-stationary vector time series observed at $t = 1, \ldots, T$. Assume that $\boldsymbol{Y}_t$ has a finite order VAR representation of the form

$$\boldsymbol{\Theta}(L)\boldsymbol{Y}_t = \begin{bmatrix} \Theta_{11}(L) & \Theta_{12}(L) \\ \Theta_{21}(L) & \Theta_{22}(L) \end{bmatrix} \begin{bmatrix} x_t \\ y_t \end{bmatrix} = \begin{bmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \end{bmatrix}, \tag{8}$$

where $\boldsymbol{\Theta}(L) = \boldsymbol{I} - \boldsymbol{\Theta}_k L - \cdots - \boldsymbol{\Theta}_p L^p$ is a 2×2 lag polynomial with $L^k \boldsymbol{z}_t = \boldsymbol{z}_{t-k}$, $\boldsymbol{I}$ is the identity matrix, and $\boldsymbol{\varepsilon}_t := [\varepsilon_{1,t}, \varepsilon_{2,t}]^\intercal$ denotes a vector white-noise process, with $E(\boldsymbol{\varepsilon}_t) = \boldsymbol{0}$ and positive-definite covariance matrix $\boldsymbol{K} = E(\boldsymbol{\varepsilon}_t, \boldsymbol{\varepsilon}_t^\intercal)$. Furthermore, we let $\boldsymbol{G}$ denote the lower triangular matrix with real and positive diagonal entries of the Cholesky decomposition $\boldsymbol{G}\boldsymbol{G}^\intercal = \boldsymbol{K}^{-1}$, such that $\boldsymbol{\eta}_t = \boldsymbol{G}\boldsymbol{\varepsilon}_t$ and $E(\boldsymbol{\eta}, \boldsymbol{\eta}^\intercal) = \boldsymbol{I}$.

If the system is assumed to be stationary, i.e., all roots of the characteristic equation $|\boldsymbol{\Theta}(L)| = 0$ are outside the complex unit circle, then there exists a moving average representation of the form

$$\begin{aligned} \boldsymbol{Y}_t = \boldsymbol{\Phi}(L)\boldsymbol{\varepsilon}_t &= \begin{bmatrix} \Phi_{11}(L) & \Phi_{12}(L) \\ \Phi_{21}(L) & \Phi_{22}(L) \end{bmatrix} \begin{bmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \end{bmatrix} \\ = \boldsymbol{\Psi}(L)\boldsymbol{\eta}_t &= \begin{bmatrix} \Psi_{11}(L) & \Psi_{12}(L) \\ \Psi_{21}(L) & \Psi_{22}(L) \end{bmatrix} \begin{bmatrix} \eta_{1,t} \\ \eta_{2,t} \end{bmatrix}, \end{aligned} \tag{9}$$

where $\boldsymbol{\Phi}(L) = \boldsymbol{\Theta}(L)^{-1}$ and $\boldsymbol{\Psi}(L) = \boldsymbol{\Phi}(L)\boldsymbol{G}^{-1}$. Based on the representation in (9), let

$$f_x(\omega) = \frac{1}{2\pi}\left\{\left|\Psi_{11}\left(e^{-i\omega}\right)\right|^2 + \left|\Psi_{12}\left(e^{-i\omega}\right)\right|^2\right\}$$

denote the spectral density of x_t. The measure of causality from y_t to x_t at frequency ω suggested by Geweke (1982) and Hosoya (1991) is defined as

$$M_{y\to x}(\omega) = \log\left\{\frac{2\pi f_x(\omega)}{\left|\Psi_{11}\left(e^{-i\omega}\right)\right|^2}\right\} = \log\left\{1 + \frac{\left|\Psi_{12}\left(e^{-i\omega}\right)\right|^2}{\left|\Psi_{11}\left(e^{-i\omega}\right)\right|^2}\right\}.$$

Within this framework, if $M_{y\to x}(\omega) = 0$, then we say that y_t does not Granger cause x_t at frequency ω. Breitung and Candelon (2006) developed a simple approach to test the null hypothesis

$$H_0 : M_{y\to x}(\omega) = 0.$$

From $\boldsymbol{\Psi}(L) = \boldsymbol{\Theta}(L)^{-1}\boldsymbol{G}^{-1}$, we can write

$$\boldsymbol{\Psi}_{12}(L) = -\frac{g_{22}\Theta_{12}(L)}{|\boldsymbol{\Theta}(L)|},$$

where g_{22} is the lower diagonal element of $\boldsymbol{G}^{-1}$ and $|\boldsymbol{\Theta}(L)|$ is the determinant of $\boldsymbol{\Theta}(L)$. Since $M_{y\to x}(\omega) = 0$ when $\left|\Psi_{12}\left(e^{-i\omega}\right)\right|^2 = 0$, it follows that y_t does not Granger cause x_t at frequency ω if

$$\left|\Theta_{12}\left(e^{-i\omega}\right)\right| = \left|\sum_{j=1}^{p}\theta_{12,j}\cos\left(j\omega\right) - i\sum_{j=1}^{p}\theta_{12,j}\sin\left(j\omega\right)\right| = 0,$$

where the $\theta_{ij,k}$'s are the coefficients of the lag polynomial $\Theta_{12}(L) = \theta_{12,1}L + \cdots + \theta_{12,p}L^p$ in (8). In this case, necessary and sufficient conditions for $\left|\Theta_{12}\left(e^{-i\omega}\right)\right| = 0$ are

$$\sum_{j=1}^{p}\theta_{12,j}\cos\left(j\omega\right) = 0, \tag{10}$$

$$\sum_{j=1}^{p}\theta_{12,j}\sin\left(j\omega\right) = 0. \tag{11}$$

The Breitung and Candelon (2006) approach is based on the linear restrictions (10) and (11) which are reformulated by writing the equation for x_t in the VAR(p) system,

$$x_t = c_1 + \sum_{j=1}^{p}\alpha_j x_{t-j} + \sum_{j=1}^{p}\beta_j y_{t-j} + \varepsilon_{1,t},$$

where $\alpha_j = \theta_{11,j}$ and $\beta_j = \theta_{12,j}$. Then the null hypothesis of $M_{y\to x}(\omega)$ is equivalent to

$$H_0 : \boldsymbol{R}(\omega)\boldsymbol{\beta} = \boldsymbol{0}, \tag{12}$$

where $\boldsymbol{\beta} = [\beta_1, \beta_2, \ldots, \beta_p]^\intercal$ and $\boldsymbol{R}(\omega)$ is a $2 \times p$ restriction matrix

$$\boldsymbol{R}(\omega) = \begin{bmatrix} \cos(\omega) & \cos\left(2\omega\right) & \cdots & \cos\left(p\omega\right) \\ \sin(\omega) & \sin\left(2\omega\right) & \cdots & \sin\left(p\omega\right) \end{bmatrix}.$$

The ordinary F test for (12) is approximately distributed as $F(2, T-2p)$ for $\omega \in (0, \pi)$, where 2 is the number of restrictions and T is the number of observations.

The framework can be further extended to accommodate to the case of additional variables. In this case, the frequency test is computed conditional on these variables. The conditioning suggested by Geweke (1984) consists of including lagged values of additional variables in the test regression. Assuming that there is only one additional variable, z_t, to test the hypothesis that y_t does not Granger cause x_t conditional on z_t at frequency ω, or $H_0 : M_{y\to x|z}(\omega) = 0$, we can run the following regression:

$$x_t = c_1 + \sum_{j=1}^{p}\alpha_j x_{t-j} + \sum_{j=1}^{p}\beta_j y_{t-j} + \sum_{j=1}^{p}\delta_j z_{t-j} + \varepsilon_{1,t}.$$

We can then apply the testing procedure on the parameters of lagged y_t, as described above.

Furthermore, Breitung and Candelon (2006) suggested that the frequency domain causality test is particularly robust for the over-parameterized level-VAR estimator developed by Toda and Yamamoto (1995) and Dolado and Lütkepohl (1996). Assuming the highest integration order based on unit root tests is d_{max}, and the optimal lag for the level VAR is p, we can write the regression test as

$$x_t = c_1 + \sum_{j=1}^{p}\alpha_j x_{t-j} + \sum_{j=1}^{p}\beta_j y_{t-j} + \sum_{j=1}^{p}\gamma_j z_{t-j} + \sum_{j=p+1}^{p+d_{max}}\alpha_j x_{t-j} + \sum_{j=p+1}^{p+d_{max}}\beta_j y_{t-j} + \sum_{j=p+1}^{p+d_{max}}\gamma_j z_{t-j} + \varepsilon_{1,t}.$$

The null hypothesis that y_t does not Granger cause x_t conditional on z_t at frequency ω, $H_0 : M_{y\to x|z}(\omega) = 0$ involving only $\beta_j, j = 1, \ldots, p$ can be tested using the MWald statistic. In our study, we use the Toda-Yamamoto MWald test within the Toda-Yamamoto framework (Tastan, 2015; Nwani et al., 2023).

The frequency-domain causality test results are shown in Figure 1. The horizontal green dotted and red dashed lines represent the critical value at 10% and 5% level of significance, respectively, for the null hypothesis of Granger non-causality at frequency ω. The solid blue line represents the statistical test values at distinct frequencies within the interval $(0, \pi)$. Causality is present at a given frequency if the plot of the test statistic values exceed the critical value. While only the graphs illustrating the causal relationship between economic growth and energy consumption are shown here, the results for the remaining variables are presented in Table 10. Following Kirikkaleli and Adebayo (2020), He et al. (2021) and Yildiz (2022), the test statistics are calculated at low frequencies of $\omega = 0.01$ and $\omega = 0.05$ to examine long-run causality, $\omega = 1.0$ and $\omega = 1.5$ to examine medium-run causality, and finally $\omega = 2.0$ and $\omega = 2.5$ to examine short-run causality. A long, medium or short-run causality relationship means that the resulting causality is permanent, intermediate, or temporary, respectively.

As shown in Figure 1a, economic growth Granger-causes electricity consumption in the frequency range of $\omega = 0.01$ to $\omega = 1.0$ and $\omega = 2.13$ to $\omega = \pi$, corresponding to cycle lengths of approximately 6 to 628 quarters, and 2 to 3 quarters, respectively. In contrast, as observed in Figure 1b, the null hypothesis of non-causality from electricity consumption to economic growth cannot be rejected across all frequency intervals. These findings, in line with the time-domain analysis, lend support to the conservation hypothesis for the case of electricity consumption in Madagascar. Furthermore, our findings align with those of Ramaharo et al. (2024) for Madagascar, who also identify a unidirectional causal relationship from economic growth to electricity consumption in the short run, using time-domain analysis.

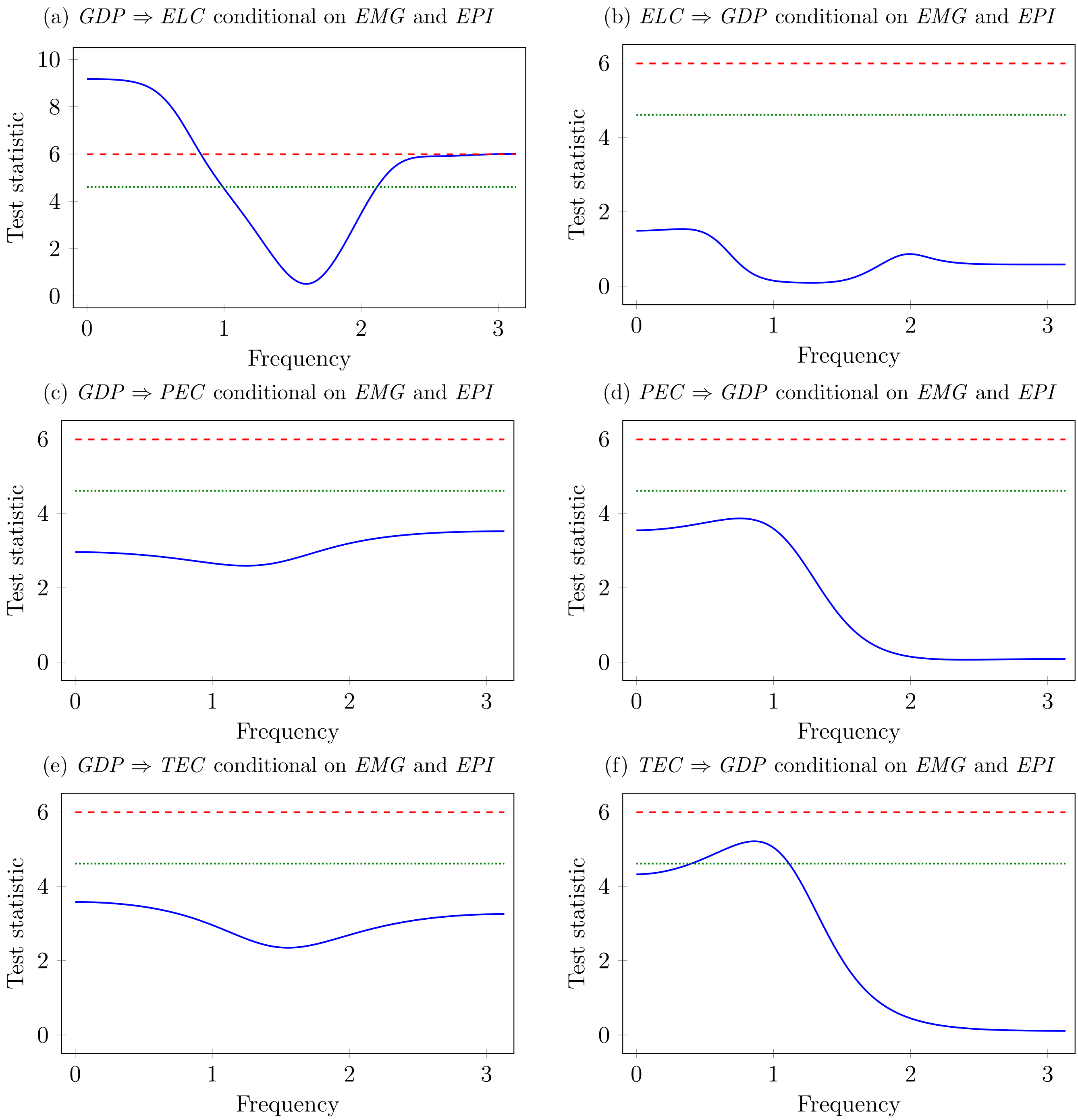
Figures 1d and 1c demonstrate that petroleum consumption and economic growth are neutral to each other in Madagascar. This means that changes in petroleum consumption do not significantly influence economic growth, and vice versa. This finding aligns with earlier time-domain results, providing further support for the neutrality hypothesis regarding petroleum consumption in the country. This suggests that efforts to reduce fossil fuel consumption, such as promoting renewable energy sources or improving energy efficiency, may not adversely impact economic growth, as long as effective policies to manage energy imports and energy prices are well implemented.

Turning now our attention to Figure 1e, we see that the null hypothesis of non-causality from economic growth to total energy consumption cannot be rejected across all frequency intervals. However, for the causality flowing from total energy consumption to economic growth (Figure 1f), we find evidence of a statistically significant linkage in the frequency band of $\omega = 0.29$ to $\omega = 1.12$, at the 10% significance level. This corresponds to cycle lengths of approximately 22 quarters (long run) and 6 quarters (medium run), supporting the growth hypothesis for total energy consumption in Madagascar. This finding, while deviating from the time-domain causality results, suggests that the Malagasy economy exhibits energy dependency on both electricity and petroleum sources for growth. The lack of individually detectable causal effects for electricity consumption and petroleum consumption separately implies that the combined use of these energy sources is crucial for stimulating economic growth in Madagascar. However, the relatively weak significance level of the detected causality suggests that the benefit or loss in growth remains contingent upon factors such as energy imports and energy prices. Further investigation into the direct causal nexus between economic growth and energy consumption at different levels of aggregation is necessary for a comprehensive understanding of their complex interplay in Madagascar.

The causal relationship between the remaining variables are summarized in Table 10. The analysis reveals a strong causal relationship between economic growth and energy prices in Madagascar, with economic growth consistently driving energy prices in both the long and medium term across all models. This finding implies that economic expansion is a permanent and significant factor influencing energy price dynamics in the country. In addition, the lack of feedback from energy prices to economic growth indicates that energy price policy may not have a direct influence on economic growth. Nevertheless, policymakers should exercise caution when implementing measures such as subsidies, which can have unintended consequences, including exacerbating income inequality. Specifically, fuel price subsidies have been shown to be a burden for public budget and primarily benefit high-income consumers, while disproportionately affecting vulnerable groups through reduced expenditures (Andriamihaja and Vecci, 2007; Sharma et al., 2019).

For Model A, there is a unidirectional causality running from energy imports to electricity consumption in both the long run and the medium run. This means that changes in the country's energy import levels have a permanent effect on its domestic electricity demand. The dominance of energy imports in driving

Figure 1: Breitung-Candelon Spectral Granger-causality test results



Note: "⇒" indicates the direction of the Granger-causality. The horizontal green dotted and red dashed lines represent the critical value at 5% and 10% level of significance, respectively, for the null hypothesis of no Granger causality at frequency $\omega \in (0, \pi)$. The solid blue line represents the statistical test values at distinct frequencies within the interval $(0, \pi)$. The VAR models are estimated with $5 + 1$ lags for Model A, and $3 + 1$ lags for Model B and C. The test is conducted using Tastan's (2015) "`bcgcausality`" command in STATA.

electricity demand raises questions about the potential effectiveness of policies focused narrowly on electricity sector management. Electricity-specific interventions may have limited impact if they do not account for this underlying dynamic of import dependency. Instead, a more holistic approach that addresses Madagascar's overall energy mix and trade relationships may be required to meaningfully manage electricity consumption. Therefore, addressing Madagascar's reliance on imported energy sources should be a priority to enhance the resilience and self-sufficiency of its electricity system (MEH, 2015).

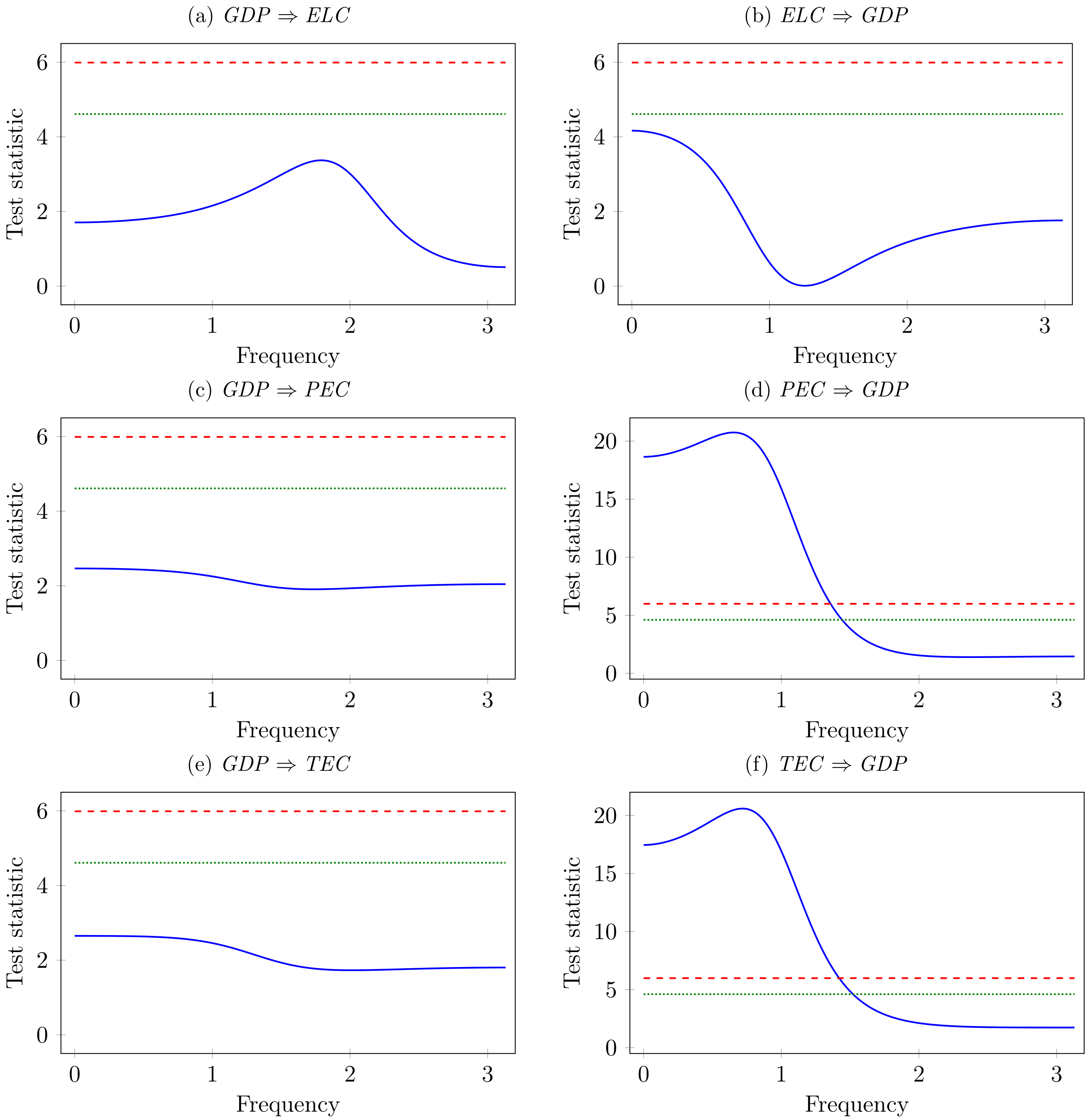
Table 10: Breitung-Candelon Spectral Granger-causality test results

Null hypothesis	**Long run**		**Medium run**		**Short run**	
	$\omega = 0.01$	$\omega = 0.05$	$\omega = 1.0$	$\omega = 1.5$	$\omega = 2.0$	$\omega = 2.5$
Model A						
$GDP \nRightarrow EMG$	6.568**	6.575**	0.877	0.032	0.298	0.379
$EMG \nRightarrow GDP$	2.075	2.069	1.285	1.165	0.121	0.452
$GDP \nRightarrow EPI$	13.210***	13.204***	10.696***	7.914**	2.164	0.872
$EPI \nRightarrow GDP$	1.046	1.035	3.899	3.161	3.210	1.580
$ELC \nRightarrow EMG$	1.468	1.478	1.379	0.499	0.247	0.012
$EMG \nRightarrow ELC$	13.992***	13.945***	7.782**	6.200**	1.447	3.907
$ELC \nRightarrow EPI$	1.663	1.667	1.737	0.417	0.714	1.302
$EPI \nRightarrow ELC$	4.513	4.517	4.239	1.283	0.106	0.267
$EMG \nRightarrow EPI$	3.726	3.725	0.512	1.487	7.271**	8.181**
$EPI \nRightarrow EMG$	1.941	1.928	1.711	1.156	0.790	0.404
Model B						
$GDP \nRightarrow EMG$	6.602**	6.595*	0.198	1.100	2.546	2.923
$EMG \nRightarrow GDP$	0.511	0.511	0.218	0.110	0.559	0.784
$GDP \nRightarrow EPI$	8.979**	8.981**	9.191**	6.012**	2.294	1.492
$EPI \nRightarrow GDP$	4.546	4.547	4.645*	4.507	4.389	4.347
$PEC \nRightarrow EMG$	17.122***	17.118***	11.371***	3.843	5.014*	6.722**
$EMG \nRightarrow PEC$	2.197	2.195	0.837	0.112	2.001	3.045
$PEC \nRightarrow EPI$	8.55**	8.549**	6.198**	1.622	1.46	2.119
$EPI \nRightarrow PEC$	0.561	0.562	1.181	1.463	1.299	1.175
$EMG \nRightarrow EPI$	3.489	3.493	5.063*	5.193*	2.374	1.162
$EPI \nRightarrow EMG$	0.291	0.292	0.328	0.293	0.257	0.244
Model C						
$GDP \nRightarrow EMG$	6.580**	6.576**	3.937	0.564	1.209	2.863
$EMG \nRightarrow GDP$	0.370	0.369	0.159	0.246	0.656	0.797
$GDP \nRightarrow EPI$	10.323***	10.325***	10.417***	6.461**	2.042	1.186
$EPI \nRightarrow GDP$	3.845	3.846	4.087	3.85	3.606	3.512
$TEC \nRightarrow EMG$	17.601***	17.594***	10.250***	2.488	4.296	6.165**
$EMG \nRightarrow TEC$	1.136	1.134	0.221	0.524	2.249	2.862
$TEC \nRightarrow EPI$	9.300***	9.300***	6.443**	1.311	1.200	1.864
$EPI \nRightarrow TEC$	0.212	0.212	0.660	1.190	1.239	1.187
$EMG \nRightarrow EPI$	3.707	3.711	5.398*	5.183*	2.267	1.136
$EPI \nRightarrow EMG$	0.322	0.322	0.310	0.235	0.203	0.197

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. "$A \nRightarrow B$" indicates that A does not Granger-cause B at frequency ω. The VAR models are estimated with $5+1$ lags for Model A, and $3+1$ lags for Model B and C. The test is conducted using Tastan's (2015) "`bcgcausality`" command in STATA.

For Models B and C, there is unidirectional Granger causality running from petroleum product consumption and total energy consumption to energy prices in both the long run and the medium run. Again, for Models B and C, there is unidirectional causality running from total energy consumption and petroleum product consumption to energy imports in the long, medium, and short runs. Additionally, while economic growth Granger-causes energy imports in the long run, no reciprocal causality is found. This contrasts with the findings of Ramaharo et al. (2024), who identified a causal relationship from energy imports to economic growth in the short run. Furthermore, there is unidirectional causality running from energy imports to energy prices across all models: for Model A, this occurs in the medium run, while for Models B and C, it occurs in the long run. Ramaharo et al. (2024), through their time-domain analysis, found a short-run causal relationship from energy prices to energy imports, which differs from our findings. This discrepancy can be attributed to the use of different variable proxies in each study, as they particularly measured energy imports as the share of energy goods imports in total goods imports, and used the consumer price index as a proxy for energy prices.

Figure 2: Breitung-Candelon Spectral Granger-causality test results (bivariate framework)



Note: "⇒" indicates the direction of the Granger-causality. The horizontal green dotted and red dashed lines represent the critical value at 5% and 10% level of significance, respectively, for the null hypothesis of no Granger causality at frequency $\omega \in (0, \pi)$. The solid blue line represents the statistical test values at distinct frequencies within the interval $(0, \pi)$. The VAR models were estimated with $4 + 1$ lags for Model A, and $3 + 1$ lags for Model B and C. The test was conducted using Tastan's (2015) "`bcgcausality`" command in STATA.

Next, in order to investigate the direct relationship between energy consumption and economic growth, we now repeat the test in a bivariate framework, excluding energy imports and energy prices. The results are displayed in Figure 2.

Both Figure 2a and 2b highlight the absence of a causal relationship between electricity consumption and economic growth at any frequency, supporting the neutrality hypothesis. Taking into consideration the conditioned case, both finding underscores the significant role of energy imports and energy prices as indirect channels of causality for electricity demand, as observed in previous analyses (see Figure 2a). The results imply that electricity consumption forecasting models for Madagascar which neglect to incorporate energy dependency variables will likely produce inaccurate projections and potentially misleading policy recommendations. Our findings corroborate those of Ghodsi and Huang (2015) for Sub-Saharan Africa. Similarly, Akça (2023) found no evidence of causality from electricity consumption to economic growth for Turkey, but instead, detected that economic growth Granger-causes electricity consumption at all frequencies. Consistent with these findings, Sica and Sentürk (2016) found no evidence of causality from electricity consumption to economic growth for Italy, but rather, identified a unidirectional causality running from economic growth to electricity consumption in the long run. Moreover, Sica and Sentürk (2016) and Yildiz (2022) also report similar results for Turkey. These findings are particularly consistent with ours when controlling for the effects of energy imports and energy prices in the causality test.

As shown in Figure 2d, strong evidence of causality running from petroleum consumption to economic growth is observed in the frequency range of $\omega = 0.01$ to $\omega = 1.45$, that is in the long and medium run. Similarly, Figure 2f reveals a unidirectional causality running from total energy consumption to economic growth in the frequency range of $\omega = 0.01$ to $\omega = 1.53$. We note that the results for Models B and C align with the conditioned case when testing for the feedback, as the test failed to reject the null hypotheses of no causality at any frequency (compare Figures 2c and 2e to Figures 1d and 1f). Hence, including energy imports and prices from the analysis does not yield any new insights into the causal relationships in these directions. These findings provide evidence in support of the growth hypothesis in the long run for Madagascar. Notably, similar results have been reported by Bozoklu and Yilanci (2013) for Finland and Greece, Ahmed and Azam (2016) for some low income countries (Kenya, Tajikistan, Tanzania and Togo), and Gorus and Aydin (2019) for Oman. While Ghodsi and Huang (2015) identified a similar causal relationship in the short run for Sub-Saharan Africa, the time-domain causality analysis conducted by Kahsai et al. (2012) revealed that energy consumption and economic growth have a neutral short-run effect on each other for a panel of 40 Sub-Saharan Africa and a subset of low income countries including Madagascar. Specifically, the findings of this study suggest that incorporating information on these energy variables alongside past GDP values enhances the prediction of future GDP. This distinct causality linkage suggests that higher total energy consumption is associated with increased value-added activities, which in turn contribute positively to Malagasy real GDP.

3 Concluding remarks

The primary objective of this study was to explore the long-run relationship between economic growth and energy consumption, including electricity, petroleum, and total energy consumption, using quarterly data for the period 2007-2022 and deploying a comprehensive conceptual framework that incorporates principal component analysis, a unit root test, a cointegration test, long-run effects estimation, and the Granger causality test. Our findings demonstrate the intricate interplay between economic growth and energy consumption, emphasizing the crucial roles of energy imports and prices in this dynamic.

First, we applied Principal Component Analysis (PCA) to three price measures–world oil prices, energy import prices, and energy consumer prices–to construct an energy price index. Next, we employed the Bayer-Hanck cointegration test, which revealed a long-run relationship between the study variables. To further investigate the impact of each factor on energy consumption, we utilized three estimation methods: Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegrating Regression (CCR). Our results consistently demonstrated a positive long-run effect of all studied factors on energy consumption, including electricity, petroleum, and total energy consumption. To ensure the validity of our estimation, we performed an additional robustness check and sensitivity test. We tested the robustness of our estimation using the Robust Least Squares (RLS) method and re-estimated the model using different price measures. Our estimates indicated that our initial results were largely insensitive to this alternative specification. This suggests that our results are quite robust overall, regardless of the choice of estimators or price specification. Furthermore, each price measure was found to have a positive effect on energy consumption, providing further confirmation of the non-conventional sign revealed by the earlier estimators. This consistency lends strong support to our findings.

To further investigate the causal relationships between economic growth and energy consumption, we employed two methods: the Toda-Yamamoto approach for Granger non-causality testing in the time domain and the Breitung-Candelon test for Granger causality testing in the frequency domain. The Toda-Yamamoto test revealed a unidirectional long-run causal effect flowing from economic growth to electricity consumption, supporting the conservation hypothesis. In contrast, the Toda-Yamamoto test did not detect any causal relationships between economic growth and either petroleum consumption or total energy consumption, lending support to the neutrality hypothesis. Furthermore, the Breitung-Candelon test provided further insights, corroborating the conservation hypothesis for electricity consumption and confirming the neutral relationship between economic growth and petroleum consumption. Interestingly, the test supported the growth hypothesis for total energy consumption, as a causal effect from total energy consumption to economic growth was uncovered in both the long and medium run. Importantly, the test highlighted the crucial role of energy imports and prices in shaping the dynamics of economic growth and energy consumption. These variables serve as mediators, strengthening the causal link between economic growth and electricity consumption when included in the analysis. Conversely, they act as confounding variables for petroleum consumption and total energy consumption, revealing a significant causal link from these variables to economic growth when energy imports and prices are not controlled for.

Our analysis particularly revealed a statistically significant positive long-run relationship between economic growth and energy consumption in Madagascar, indicating that economic expansion inevitably leads to increased energy demand. To ensure a sustainable energy future, Madagascar must make a strategic choice: rely on imported conventional energy, or prioritize domestic renewable energy development. The implementation strategy of the New Energy Policy clearly outlines Madagascar's commitment to ensuring energy security and independence. This involves diversifying the energy mix, reducing hydrocarbon imports, and prioritizing the development of local energy resources, particularly those of renewable origin (MEH, 2015). While imported energy provides immediate access to resources, it exposes Madagascar to price volatility and supply disruptions. Conversely, prioritizing domestic renewable requires significant upfront investment and infrastructure development. If Madagascar continues to rely on imported energy, a multifaceted policy is essential, including diversifying energy suppliers to mitigate reliance on any single source, fostering regional energy cooperation to access diverse energy resources and facilitate cross-border energy trade, and diversifying imported energy sources to reduce dependence on fossil fuels (Kim et al., 2024). Policies and incentives should be reinforced to encourage the import of renewable energy technologies and equipment, further bolstering energy resilience. However, if domestic energy supply is prioritized, Madagascar should capitalize on its abundant solar radiation, wind resources, and hydro-power potential, which offer significant opportunities for domestic renewable energy development (Praene et al., 2017; Surroop and Raghoo, 2018; Batinge et al., 2019; Nematchoua, 2021). One effective approach to achieve this is to gradually realign oil price subsidies towards sustainable energy initiatives (Ahuja and Tatsutani, 2009; Shittu et al., 2024). This would, for example, free up resources to strengthen and interconnect electric power transmission networks in Madagascar, enhancing energy security and facilitating the integration of renewable energy sources, particularly in rural areas currently lacking reliable modern energy (Prasad, 2011).

This study contributes to the limited empirical research on Madagascar's energy-economic growth nexus by analyzing available data and comparing findings with existing literature. Understanding the relationship between economic growth and energy consumption is crucial for developing effective growth strategies, implementing appropriate energy policies, and monitoring their effectiveness. This is particularly important for Madagascar, given its heavy reliance on foreign energy sources and its vast potential for renewable energy. The study reveals insights into the energy-growth nexus, informing decisions related to energy investments, resource allocation, and the development of sustainable energy solutions. However, the study is limited by data availability, focusing only on electricity and petroleum consumption. Expanding the investigation to include a broader range of energy sources would provide more comprehensive insights, enabling a more robust understanding of the energy-growth relationship and informing policymakers in designing effective energy security and transition strategies for sustainable development.

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