METU

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ABSTRACT

Countries do not only want to increase their production but also they want to jump to a higher level of performance. Making that jump depends on technology, which can be built in two ways: by investing in knowledge (research and development) and by investing in physical assets (gross capital formation). This study asks how much each kind of spending helps the United States improve its GDP. Using annual data for 1996-2022, we apply time-series techniques,unit-root tests, an ARDL bounds approach, and an error-correction model, also the usual checks for serial correlation, heteroskedasticity, and parameter stability. The results show that R&D spending decrease GDP growth at first but increase GDP growth in medium run, while physical capital spending supports growth mainly in the short run. Overall, knowledge investment and capital formation work together and both matter for economic growth.

1. INTRODUCTION

Economic growth is not just about adding a few more machines or putting people to work. It is about making a shift to a higher level of productivity. There are two main investment that shift production to higher. First, spending on research and development (R&D) builds knowledge capital. R&D is the ideas, designs and know-how that increase the production frontier outward. Second, spending on new plant, equipment and inventories and it is recorded in the national account as gross capital formation. Gross Capital Formation expands the stock of physical capital that turn ideas into practice. Both ways are important, but theory gives them different roles. Classic (neoclassical) growth models see physical capital as the engine of short-run development. On the other hand, endogenous-growth models believe sustained growth coming from new ideas produced by R&D. Testing how the two ways work together in an economy which can therefore show the results of both theories.

United States is the world's largest spender on R&D, about $890 billion in 2022, roughly a quarter of global R&D activity (NCSES, 2025). At the same time, the United States continues to share the one-fifth of its GDP to gross capital formation (World Bank, 2025). This mix of heavy knowledge investment and physical investment makes the U.S. an ideal candidate for our question.

We gather an annual data set for 1996-2022. We estimate an autoregressive distributed-lag (ARDL) model that catch both short- and long-run effects of variables. Transforming model and diagnostic tests of models gives reliable results. A test of integrated of order lead to an ARDL bounds test confirms cointegration among real GDP, R&D, lagged of R&D, and gross capital formation. Adding this relationship into an error-correction model, we find a significant adjustment term and validate the results with standard diagnostics for serial correlation, heteroskedasticity and parameter stability. The resulting coefficients reveal how knowledge and physical capital each contribute separately and jointly to U.S. economic growth.

After briefly discussing theories and studies in literature review, we will give the data from World Development Indicator from World Bank website. After finding best model, we will interpret the result according to beliefs and theories.

2. LITERATURE REVIEW

The theoretical link between R&D expenditures, gross capital formation, and economic growth is grounded in two main strands of growth theory. First, endogenous growth models argue that investments in knowledge capital result in long-run productivity. Romer (1990) shows that R&D generates nonrival "knowledge capital," which firms can use to raise output without lowering returns at the aggregate level. Likewise, Aghion and Howitt (1992) develop a Schumpeterian growth model where monopolistic rents on innovations motivate continuous productive activity. In both models, higher R&D leads to sustained expansions of the production frontier.

Second, the neoclassical Solow model emphasizes the role of physical capital accumulation. In Solow's (1956) formulation, economies converge toward a steady state determined by the saving rate, population growth, and exogenous technological progress. An increase in the gross investment-to-GDP ratio raises the capital-output ratio and shifts the steady-state upward, yielding permanently higher output per worker (Solow, 1956). Although technological change in this model is exogenous, the mechanism highlights investment is crucial for short- and medium-term growth.

Many studies find positive effects of R&D on GDP growth rates. Coe and Helpman (1995) employ regressions for over 20 OECD countries and report that both domestic and foreign R&D overflows contribute significantly to per-capita output growth ($p<0.01$). Their estimates suggest that a one-percent increase in world R&D stock raises a country's annual growth rate by roughly 0.04 percentage points. Focusing on the United States, Hall and Mairesse (2006) use firm-level ARDL models to deploy short- and long-run impacts of R&D intensity on total factor productivity. They find that a 1% rise in R&D spending yields a delayed but statistically significant productivity gain of approximately 0.15% in the long run.

Similarly, numerous studies link higher investment rates to faster economic expansion. Barro (1990) runs regressions across 98 countries, reporting that a one-point increase in the Investment/GDP ratio increases per-capita growth by about 0.1 percentage points annually. At the more micro level, Kneller, Bleaney, and Gemmell (1999) investigate U.S. states. They conclude that gross capital formation has a positive and significant effect even in the short run, with persistence over subsequent periods and their findings indicate that state-level investment shocks explain roughly 20% of the variance in growth rates after controlling for human capital and initial income levels.

While the separate effects of R&D and gross capital formation are well researched, there is no study about simultaneously compared their joint impacts on U.S. growth. Previous works either treat R&D as an isolated knowledge input or aggregates all types of investment into a single physical capital measure. This paper fills that gap by estimating ARDL bounds approach for the U.S. economy over 1996 to 2022, incorporating both R&D expenditures and gross capital formation to evaluate their relative importance in the short and long run.

3. DATA SOURCES AND DESCRIPTION

In this study, data are taken from World Development Indicator (WDI) from World Bank website, a globally trustable data provider. Data is between 1996-2022. There are United States GDP growth data annually and R&D spending as a percentage of GDP annual, and Gross Capital Investment as a percentage of GDP annual. The variable names, definitions, parameters that will be used in the regression, the unit of measurement and data sources are listed below.

Variable	**Indicator Code**	**Definition**	**Parameter Used**	**Units of Measurement**	**Data Source**
		The annual GDP growth rate shows how much GDP has changed in percentage terms from one year to the next,	$GDPG_t$		

GDP growth (annual %)	NY.GDP.MKTP.KD.ZG	using constant 2015 local-currency prices (converted to U.S. dollars).		Percentage (%)	World Bank
R&D expenditure (% of GDP)	GB.XPD.RSDV.GD.ZS	Gross domestic R&D spending is shown as a percentage of GDP. Covers capital and current spending by business, government, higher-education and private non-profit sectors; includes basic, applied and experimental research.	$R\&D_t$	Percentage (%)	World Bank
Gross capital formation (% of GDP)	NE.GDI.TOTL.ZS	Gross capital formation (formerly gross domestic investment) is the sum of spending on new fixed assets and the net change in inventories. Fixed assets include land improvements, machinery and equipment, and construction of infrastructure and buildings (schools, offices, homes, etc.).	GCF_t	Percentage (%)	World Bank

Source: World Development Indicators (WDI) of the World Bank from http://data.worldbank.org/

4. MODEL ESTIMATION AND HYPOTHESIS TESTING

We have time series from 1996 to 2022. We can build our multiple linear regression. In this model we have GDP growth as the dependent variable (regressand) and research and development(R&D) as percentage of GDP and Gross Capital Formation as a percentage of GDP (regressors). Our hypothetical equation is:

Hypothetical equation (1): $\mathrm{GDPG_t} = \beta_0 + \beta_1 \mathrm{R\&D_t} + \beta_2 \mathrm{GCF_t} + \varepsilon_t$

Where,

$GDPG_t$ = GDP Growth rate

$R\&D_t$ = Gross domestic R&D spending, as a percentage of GDP

GCF_t = Gross capital formation, as a percentage of GDP

ε_t = disturbance term

Using python with *statsmodels* and we run the ordinary least squares (OLS) estimation according on the United States data from 1996 to 2022. We obtain the estimated linear model below:

Model.1 : $$GDPG_t = -10.3001 - 0.5331 * R\&D_t + 0.6625\, GCF_t + \varepsilon_t$$

$$(-1.663) \qquad (-0.504) \qquad (2.932)$$

(The values given in parentheses are t-ratios for the relevant coefficients.)

The Standart Errors:

$SE(\beta_0) = 6.193$, $SE(\beta_1) = 1.058$, $SE(\beta_2) = 0.226$

R-squared (R^2):	0.293
Adj. R-squared (R_{adj}^2):	0.234
F-statistic	4.963
AIC:	106.1
Durbin-Watson:	2.145

4.1. Model Acceptability

The model has 27 annual observations, and the OLS regression estimates three parameters ($k = 3$).

Hence, the critical value for t-test is $t_{24,0.05} = \pm 2.064$.

The test statistic for each slope is:

$$\mathbf{t_i = \hat{\beta} - 0 / SE(\hat{\beta})}$$

Hypothesis:

$H_0 : \beta_i = 0$

$H_1 : \beta_i \neq 0$

Gross Capital Formation has a t- statistic of 2.932. As 2.932 > 2.064, we reject null hypothesis. Thus, GCFt is individually significant at 95 confidence level.

$R\&D_t$ has a t value of -0.504. As |-0.504| < 2.064, we fail to reject the null hypothesis, so $R\&D_t$ is not individually significant.

Another important term is that we should check the joint significant of explanatory variables to see if they are significant as a group. We test the joint significant of variables by F-test.

$$F = \frac{SSR}{\frac{SSE}{n-k-1}}$$

$H_0 : \beta_1 = \beta_2 = ... = \beta_k = 0$

H_1 : at least $\beta_i \neq 0$

The critical value for F-test is $F_{2,27}^{0.05} = 3.35$

Since 4.96 > 3.35, we reject the null hypothesis, so model is jointly significant.

4.2. Theory Consistency

According to growth theory, both R&D spending and Gross Capital Formation should increase the GDP Growth. In our static OLS results, the sign and size of the Gross Capital Formation coefficient is compatible with the theories. One percentage point increase in GCF boost the GDP Growth by 0.66 percentage. This finding fits with Solow Model and common belief, that is more factories, machines, and inventories increase the GDP Growth.

On the other hand, the coefficient of the R&D is -0.5331 and statistically insignificant. It shows that one percentage point increase in the R&D will decrease the GDP growth by 0.53 percentage. At first it may seem the opposite of endogenous-growth theory. However, this was not unexpected because increase in R&D shows it effects after some time. This is because a new idea needs time to turn into practice.

To capture lagged effects and build a more reliable model, we need to transform the model.

4.3. Model transformation

Model.1 could not catch the delayed effect from R&D investment, so we add one lag of R&D to the equation. The new model:

Hypothetical equation (2): $\mathrm{GDPG_t} = \beta_0 + \beta_1\ \mathrm{R\&D_t} + \beta_2\ \mathrm{R\&D_{t-1}} + \beta_3\ \mathrm{GCF_t} + \varepsilon_t$

Model.2 : $\mathrm{GDPG_t} = -23.7286 - 15.0039 * \mathrm{R\&D_t} + 17.5785 * \mathrm{R\&D_{t-1}} + 0.9194\ \mathrm{GCF_t} + \varepsilon_t$

(-3.846) (-3.702) (3.693) (4.682)

(The values given in parentheses are t-ratios for the relevant coefficients)

The Standart Errors:

$SE(\beta_0) = 6.170$, $SE(\beta_1) = 4.052$, $SE(\beta_2) = 4.760$, $SE(\beta_3) = 0.196$

R-squared (R^2)	0.562
Adj. R-squared (R_{adj}^2)	0.503
F-statistic	9.424
AIC	92.41
Durbin-Watson	1.823

With 27 observation and 4 estimated variables, $t_{23,0.05} = 2.064$.

Since every coefficient exceeds the critical value, $R\&D_t$, $R\&D_{t-1}$, and GCF_t are all individually significant at 95 confidence level.

As critical value of F test is $F_{3,27}^{0.05} = 2.96$. Since $9.24 > 2.96$, the model is jointly significant.

Moreover, Model.2 has scored better R^2, Adjusted R^2, and F-statistic.
We can see that the real effect of R&D is that 17.5785 – 15.0039 = 2.5746. Also, this result does not contradict the endogenous-theory but also support the theory.

5. MODEL DIAGNOSTIC TEST

At previous section we have seen that Model.2 is better than Model.1. Thus, we will continue with Model.2

5.1. Heteroscedasticity

OLS assumes that the disturbance term does not vary:

$$\mathrm{Var}[\varepsilon_i] = \sigma^2 \quad \text{for } i = 1, \ldots, N$$

Heteroscedasticity means that the variance differs across observations. This violates the Gauss Markov assumption and makes standard errors unreliable.

We will test heteroscedasticity by Breusch-Pagan and White Test:

➔ **Breus- Pagan**

H_0 : Homoscedasticity

H_A : Heteroscedasticity

Breusch–Pagan test p-value: 0.3323

Since p-value= 0.33 > significance level = 0.05, we fail to reject the H_0 and there is no heteroscedasticity evidence.

➔ **White Test**

H_0 : Homoscedasticity

H_A: Heteroscedasticity

White test p = 0.3533

Since p-value= 0.35 > significance level = 0.05, we fail to reject the H_0 and we have seen that there is no heteroscedasticity by also WHITE test.

Thus, *Model.2 satisfies the homoscedasticity assumption of OLS*

5.2. Autocorrelation (Serial Correlation)

OLS assumes that today's residuals are not correlated with early residuals:

$$\mathrm{Cov}(\varepsilon_i, \varepsilon_j) = 0 \quad \forall i \neq j.$$

Autocorrelation occurs when the residual at time t is correlated with residual at t-1. When there is a autocorrelation in a model, the model is not reliable because the standard errors of the coefficient estimates will be biased.

We will investigate the autocorrelation in Model.2.

AR (1) process:

$u_t = p\, u_{t-1} + e_t$

where, e_t is a white noise disturbance term.

If p > 0, there is positive autocorrelation,

If p < 0, there is negative autocorrelation and

If p = 0, there is no autocorrelation

→ Durbin-Watson Test

Durbin-Watson statistic lies between 0-2 for positive serial correlation, around 2 for first-order autocorrelation, and 4 for negative correlation.

$$d = \frac{\sum_{t=2}^{T}(e_t - e_{t-1})^2}{\sum_{t=1}^{T} e_t^2}$$

Durbin-Watson Test Result: 1.823

Since 1.823 is very close to 2, we fail to reject the null hypothesis of no first-order autocorrelation.

→ **Breusch–Godfrey Test**

Breusch–Godfrey higher order serial correlation by regressing original residual on its own lags and the model's regressors.

Auxiliary regression(1): $\hat{u}_t = \alpha_0 + \alpha_1 \hat{u}_{t-1} + \beta_1 \text{ R\&D}_t + \beta_2 \text{ R\&D}_{t-1} + \beta_3 \text{ GCF}_t + \varepsilon_t$

H_0: $\alpha_1 = 0$

H_A: $\alpha_1 \neq 0$

Auxiliary R^2: 0.0055

Effective sample size (T′): 25

LM statistic ($R^2 \times T'$): 0.1381

Critical value $\chi^2_{1,\,0.95}$: 3.8415

Since LM = 0.1381 < 3.8415, we fail to reject H_0. There is no evidence of first-order autocorrelation.

Auxiliary regression(2): $\hat{u}_t = \alpha_0 + \alpha_1 \hat{u}_{t-1} + \alpha_2 \hat{u}_{t-2} + \beta_1 \text{ R\&D}_t + \beta_2 \text{ R\&D}_{t-1} +$
$+ \beta_3 \text{ GCF}_t + \varepsilon_t$

H_0: $\alpha_1 = \alpha_2 = 0$

H_A: $\alpha_i \neq 0$

LM test p-value is equal to 0.8007. Since $0.8007 > \alpha = .05$, we fail to reject H_0. There is no serial correlation up to second order of Model.2.

Both the Durbin–Watson and the Breusch–Godfrey tests shows that Model.2 don't have significant autocorrelation.

Model.2 satisfying the OLS requirement of uncorrelated residuals

6. TIME SERIES

Hypothetical equation (2): $GDPG_t = \beta_0 + \beta_1 R\&D_t + \beta_2 R\&D_{t-1} + \beta_3 GCF_t + \varepsilon_t$

6.1. Determining the Order of Integration of Variables

Before estimating a dynamic model, we must establish the order of integration of each variable. To determine the order, we will use Augmented Dickey Fuller to test unit root in each variable. We apply the ADF test with only constant specification and the optimal number of lags was chosen automatically by the Akaike Information Criterion (AIC).

ADF hypothesis:

H_0: Unit root exists

H_A: No unit root

Variable	ADF Statistic p-value	Model	H_0	First Difference ADF p-value	Model for First Difference	H_0 at first difference	Conclusion
$GDPG_t$	0.0003	constant	Rejected	0.0000	constant	Rejected	I(0)
$R\&D_t$	0.9990	constant	Fail to Reject	0.0417	constant	Rejected	I(1)
GCF_t	0.1170	constant	Fail to Reject	0.0065	constant	Rejected	I(1)

6.2. Cointegration

Hypothetical equation (2): $\mathrm{GDPG_t} = \beta_0 + \beta_1\, \mathrm{R\&D_t} + \beta_2\, \mathrm{R\&D_{t-1}} + \beta_3\, \mathrm{GCF_t} + \varepsilon_t$

Cointegration test will show us that if there is a long-run relationship between variables. Since R&D and GCF are I(1) while GDPGt is I(0), we cannot use Engle-Granger method to test cointegration. Instead, we will use ARDL Bounds test which gives flexibility of mixed order of integration models.

We estimate an ARDL(p,q_1,q_2) model:

Hypothetical equation (3):

$$\Delta GDPG_t = \alpha_0 + \sum_{i=1}^{p} \phi_i\, \Delta GDPG_{t-i} + \sum_{j=0}^{q_1} \theta_{1j}\, \Delta R\&D_{t-j} + \sum_{k=0}^{q_2} \theta_{2k}\, \Delta GCF_{t-k} + \lambda_1\, GDPG_{t-1} + \lambda_2\, R\&D_{t-1} + \lambda_3\, GCF_{t-1} + \varepsilon_t$$

. Δ denotes first differences.

. p, q_1, q_2 are chosen by AIC.

. λ_1, λ_2, λ_3 capture the long-run levels relationship.

We test whether the lagged levels enter the equation jointly:

H_0: $\lambda_1=\lambda_2=\lambda_3=0$ (no cointegration)

H_1: At least one of λ_1, λ_2, $\lambda_3 \neq 0$ (cointegration exists)

Using F-statistic for the joint significant:

If F> upper bound, reject H0 → **cointegration exists**

If F< lower bound, fail to reject H_0 → **no cointegration**
If F lies between bounds → **inconclusive**

Model.3:

$\Delta GDPG_t$= -17.6220 - 8.3036$\Delta R\&D_t$ + 1.7027ΔGCF_t -1.2488$GDPG_{t-1}$ + 1.1684$R\&D_{t-1}$ + 0.8289GCF_{t-1} + e_t

λ_1= -1.249, λ_2 = 1.168, λ_3= 0.829 , so $\lambda_1,\lambda_2,\lambda_3 \neq 0$

Also, F= 23.10 > 5.06, we reject the null hypothesis and conclude that a long-run cointegration exists.

6.3. ECM

Since the ARDL-Bounds test confirmed the cointegration among GDP Growth, R&D and GCF (F = 23.1 >5.06), we have the below Error Correction Model:

Hypothetical equation (4):

$\Delta GDPG_t = \gamma_0 + \vartheta_1 \Delta R\&Dt + \vartheta_2 \Delta GCFt + \alpha\, EC_{t-1} + \varepsilon_t$

Where the error correction term is:
$EC_{t-1} = GDPG_{t-1} - \beta_1 R\&D_{t-1} - \beta_2 GCF_{t-1}$

and the long-run coefficients:
$\beta_1 = -\lambda_2/\lambda_1$, $\beta_2 = -\lambda_3/\lambda_1$

Where

λ_1 = -1.249, λ_2 = 1.168, λ_3 = 0.829

We have below hypothesis:

H0: $\alpha=0$(no error-correction, no long-run equilibrium force),

H1: $\alpha<0$(deviations are corrected over time).

A statistically significant negative α confirms that GDP growth adjusts back toward its long-run equilibrium whenever a shock pushes it away.

We have the estimated ECM model:

Model.4:

$$\Delta GDPG_t = \underset{(3.842)}{11.1261} - \underset{(-1.211)}{6.2496}\, \Delta R\&D_t + \underset{(2.324)}{0.9025}\, \Delta GCF_t - \underset{(-3.692)}{0.5649} EC_{t-1} + \varepsilon_t$$

(The values given in parentheses are t-ratios for the relevant coefficients)

➔ Short-run dynamics

$\Delta R\&D_t$: $\theta_1=-6.25$ and $t = -1.21$, $p > 0.005$. R&D shocks show a negative immediate effect but it is statistically insignificant.

ΔGCF_t : $\theta_2= 0.90$ and $t = 2.324$, $p < 0.005$. A 1 percentage point rise in GCF raises current GDP growth by 0.9 percentage point.

➔ Error correction

EC_{t-1} : $\alpha=-0.565$ and $t = -3.692$, $p < 0.005$. This indicates that roughly 56 % of any deviation from the long-run equilibrium is corrected within one year.

These results show us that while gross capital formation has an immediate positive effect on growth, R&D' s benefit rises over time as captured by the adjustment process back toward the long-run path.

6.4. ECM Transformation

Our initial ECM model failed to capture delayed effect of R&D. As we did previous section, we will add lagged variable of R&D to capture delayed effects.

Hypothetical Equation (5):

$$\Delta GDP_t = \gamma_0 + \theta_1 \Delta R\&D_t + \theta_2\, \Delta R\&D_{t-1} + \theta_3\, \Delta GCFt + \alpha\, EC_{t-1} + \varepsilon_t$$

Model.5:

$$\Delta GDP_t = \underset{(2.807)}{7.5843} - \underset{(-2.843)}{14.3869}\, \Delta R\&D_t + \underset{(3.241)}{16.3035} \Delta R\&D_{t-1} + \underset{(3.525)}{1.2277} \Delta GCFt - \underset{(-2.831)}{0.3983} EC_{t-1} + \varepsilon_t$$

(The values given in parentheses are t-ratios for the relevant coefficients)

Short-run dynamics

- ➔ $\Delta R\&D_t$: $\theta_1 = -\ 14.3869$ and $t = -2.84$, $p < 0.01$. One percentage point increase in R&D shows a negative and statistically significant immediate effect.

- ➔ $\Delta R\&D_{t-1}$: $\theta 2 = 16.3035$ and $t = 3.24$, $p < 0.01$. One year later, one percentage point rise in R&D raises current GDP growth by 16.3 percentage point.

- ➔ $\Delta GCFt$: $\theta 3 = 1.2277$ and $t = 3.53$, $p < 0.01$. A 1 percentage point increase in gross capital formation increases the GDP growth by 1.2 percentage point.

Error correction

- ➔ EC_{t-1} : $\alpha = -\ 0.3983$ $t = -2.83$, $p < 0.01$. This indicates that about 40 % of any deviation from the long-run equilibrium is corrected within one year.

These results show us that while R&D expenditure initially decrease GDP growth, after one year its overall effect is positive, 16.3 – 14.39 = 1.91. Gross capital formation still delivers an immediate positive effect on GDP Growth. The significant negative Error correction term ensures that any short-run shocks are largely eliminated over time.

6.5. ECM Diagnostic Test

We will do diagnostic test to our last best model.5 see if the best model is trustable.

→Ramsey's RESET Test

H_0: The functional form is correctly specified (no omitted nonlinearities).

H_1: The model is mis-specified (omitted nonlinear or interaction terms).

Since $F = 0.786$, $p = 0.471$ (> 0.05), We fail to reject H_0.

Ramsey Test shows there is no evidence of functional-form misspecification.

→White Heteroskedasticity Test

H_0: Residuals are homoskedastic (constant variance).

H_1: Residuals exhibit heteroskedasticity.

Since $LM = 21.48$, $p = 0.0899$ (> 0.05), we fail to reject H_0.

White test shows no significant heteroskedasticity.

→ Breusch–Godfrey Autocorrelation Test (up to lag 2)

- **H_0:** No serial correlation in residuals.
- **H_1:** Serial correlation present.

Since $LM = 5.94$, $p = 0.0870$ (> 0.05), we fail to reject H_0

Residuals show no evidence of first- or second-order autocorrelation.

→ARCH Test

- **H_0:** No ARCH effects (no conditional heteroskedasticity).
- **H_1:** Presence of ARCH effects.

Since $LM = 1.876$, $p = 0.171$ (> 0.05), we fail to reject H_0.

No ARCH clustering in the residual variance.

→CUSUM Test

H_0: Model coefficients are stable over time.

H_1: Structural breaks or parameter instability exist.

Since CUSUM stat = 0.860, p = 0.451 (> 0.05), we fail to reject H_0.

No evidence of structural breaks, so parameters remain stable.

→Jarque–Bera Normality Test

H_0: Residuals are normally distributed.

H_1: Residuals deviate from normality.

Since JB = 0.020, p = 0.991 (> 0.05) , we fail to reject H_0.

Residuals appear to follow a normal distribution.

→Multicollinearity (Variance Inflation Factor)

Score of VIF less than 5 shows no serious multicollinearity.

Results:

- $\Delta R\&D_t$ VIF = 1.76
- ΔGCF_t VIF = 1.17
- $\Delta R\&D_{t-1}$ VIF = 1.73
- $EC_{la}g$ VIF = 1.53

Since all VIFs are well below 5, there is no problem of multicollinearity.

Our transformed ECM Model.5 passes all diagnostic tests. This confirms that Model.5 is correctly specified, efficient, and reliable for inference on both short-run and long-run dynamics.

7. CONCLUSION

We have examined how two key channels of investment which are research & development and gross capital formation jointly affect U.S. real GDP growth over the period 1996–2022. Using an ARDL–Error Correction model, we found that:

→ Gross capital formation shows an immediate increase to GDP growth. A one percentage point rise in GCF raises annual growth by 0.9 percentage points.

→R & D spending initially appears to show negative effect on growth but after one year it increase the GDP growth by around 16 percentage point. The final effect of the R&D is around 1.91 percentage point.

→The error-correction term is –0.40. This indicates that about 40 % of any short-run deviation from the long-run relationship is eliminated within one year.

Diagnostic tests confirms that the final ECM model is free of serial correlation, heteroskedasticity, non-normality, structural breaks, and multicollinearity. The visual diagnostics are in our appendix.

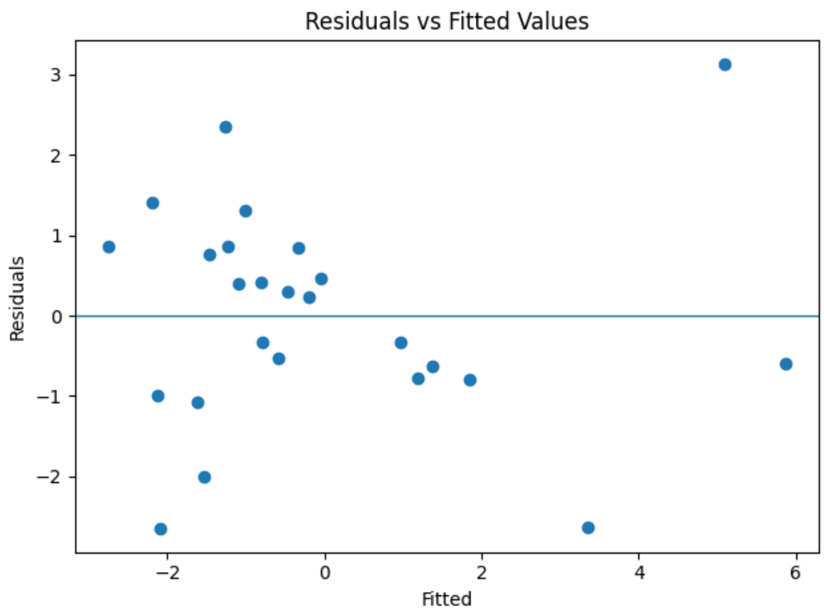
→ Policy implications

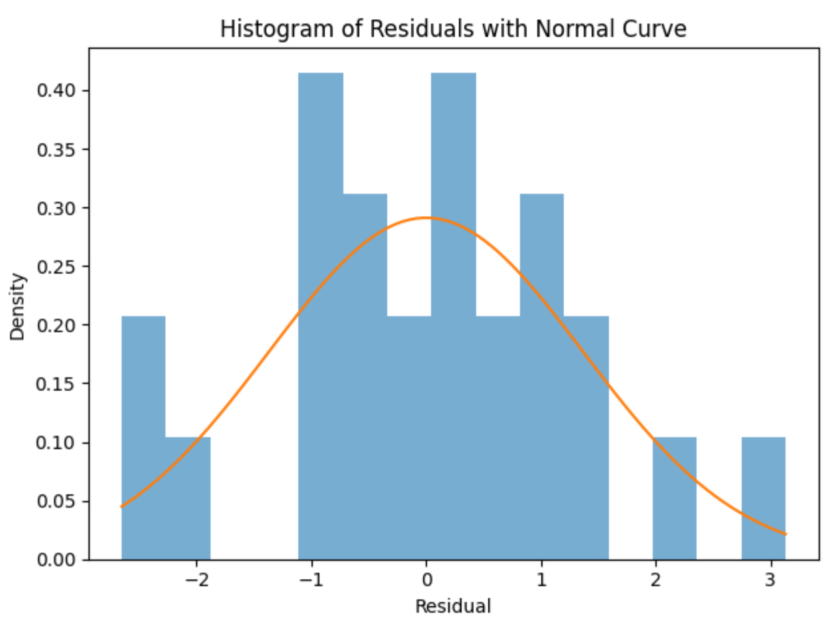
Physical investment is still crucial for immediate output gains and it should be supported throughinfrastructure spending and capital-investment incentives. At the same time, the large, delayed payoff from R&D spending needs for sustained support of innovation so that today's knowledge investments can turn into tomorrow's productivity growth. A balanced policy mix that combines short-run stimulus for physical capital with long-run incentives for knowledge creation will best promote sustained U.S. economic expansion.

→ Limitations and future research

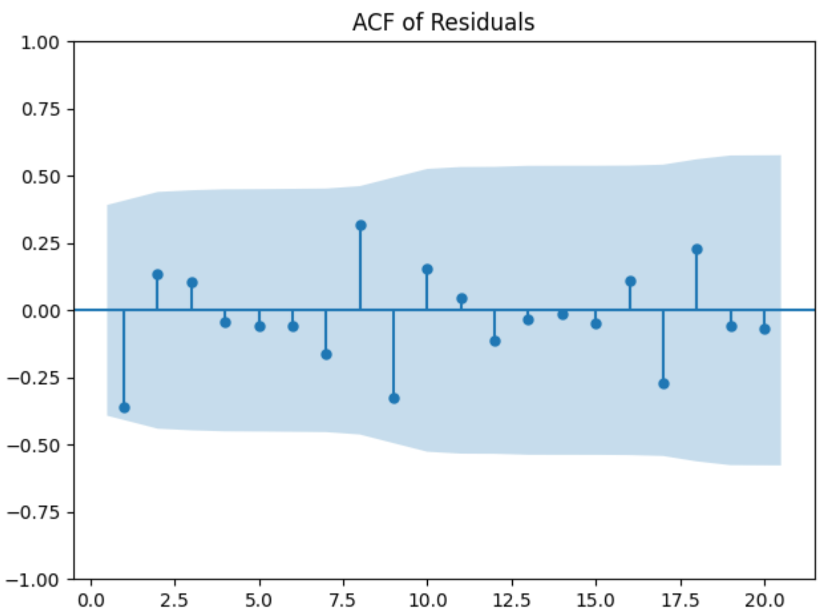
Our analysis uses annual, aggregate data for a single country. Future work could extend this framework to a panel to invstigate more detailed dynamics. Nonetheless, this paper gives an idea to further works.

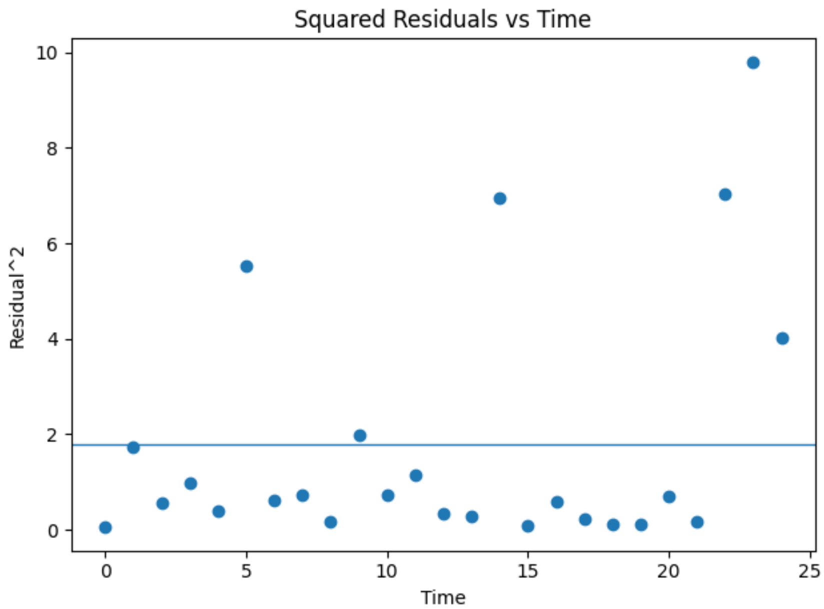
8. APPENDIX

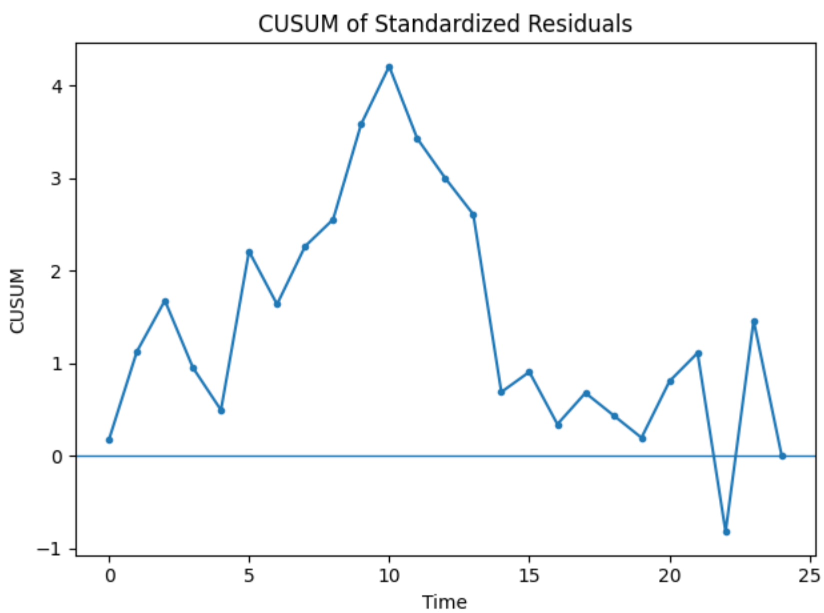

Residuals vs Fitted Values
Residuals
Fitted
3
2
1
0
−1
−2
−2
0
2
4
6


Histogram of Residuals with Normal Curve
Density
Residual
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
−2
−1
0
1
2
3


QQ Plot of Residuals
Sample Quantiles
Theoretical Quantiles
−2
−1
0
1
2


ACF of Residuals
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0





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