RESEARCH REVIEW JOURNALS
Volume-04
Issue-04
April -2019

ISSN: 2455-3085 (Online)
RESEARCH REVIEW International Journal of Multidisciplinary
www.rrjournals.com [UGC Listed Journal]

Expanding the Domain of Economics to Include Knowledge and Nature for Welfare of the Forthcoming Generations– A Review of Economic Ideas of Paul M. Romer and William D. Nordhaus

Dr. Anamika Kaushiva

Associate Professor, Economics, Sahu Ram Swaroop Mahila Mahavidyalaya, Bareilly, Uttar Pradesh (India)

ARTICLE DETAILS

Article History
Published Online: 15 April 2019

Keywords
Endogenous Technological Change, Ideas, Positive and Negative Spillovers, Global Warming, DICE, IAMs.

***Corresponding Author**
Email: econanamika[at]gmail.com

ABSTRACT

Macro economic analysis today is focusing beyond short-run perspectives of the economy - growth rate, optimum savings and business cycles - on the long-run perspective of economic growth which is concerned with human welfare of the current as well as the coming generations across the globe. Paul M. Romer and William D. Nordhaus have been awarded the Nobel Prize in Economics in 2018 for expanding the domain of growth economics by including new variables–knowledge and climate change. Romer studied the ‘Positive Externalities’ of economy i.e. ‘knowledge spillovers of endogenous technological change’ and the role of new ideas in long run economic growth. Nordhaus, on the other hand, highlighted ‘Negative Externalities’ - greenhouse-gas emissions and carbon concentration - and their impact on global climate and presented the ‘Integrated Assessment Models’. Both laureates have based their study on Robert Solow’s neoclassical growth theory for which he was awarded the 1987 Economics Prize. Beginning from the Solow model they attempt to overcome its shortcoming - an exogenous steady path of economic growth - in a different approach and reach conclusions which have a common string. Romer has argued that ‘new ideas’ promote economic growth because they have the potential to cause positive spillover or a positive externality. Nordhaus has added new dimensions to the Solow model by integrating into it the fundamental challenges the global economy was facing due to climate changes. Using Integrated Assessment Models (IAMs), and Dynamic Integrated Climate Economy (DICE) model he assesses carbon emissions and atmospheric carbon concentration level and its impact on economic growth. Romer's and Nordhaus's research opened up areas of further research on technological change and the climate-economy. This paper briefly outlines their contributions to growth economics.

1. Introduction

Global long run economic development and welfare has emerged as a fundamental issue today and encompasses multifaceted issues like growth, inclusion, sustainable development. Paul M. Romer and William D. Nordhaus have expanded the domain of growth economics beyond the variables of consumption, saving, investment, capital accumulation and have included new variables in its domain – human capital (knowledge) and nature (climate change).

Macro economic analysis preceding them focused on the short-run perspective on the economy - growth rate, optimum savings and business cycles. The long-run perspective of economic growth is much broader as it is concerned with human welfare of the current as well as the coming generations across the globe. Romer and Nordhaus, in their analysis of long-run global welfare, concentrate on a specific ‘externality’ and state that government intervention is necessary to achieve optimal growth for the future generations. Romer studies the ‘Positive Externalities’ of economy i.e. ‘knowledge spillovers of endogenous technological change’ and concludes that government policy is needed for redirecting technological changes. Nordhaus, on the other hand, highlights ‘Negative Externalities’ - greenhouse-gas emissions and carbon concentration - and their impact on global climate and through ‘Integrated Assessment Models’ suggests policy measures.

Both laureates have based their study on Robert Solow’s neoclassical growth theory for which he was awarded the 1987 Economics Prize. Beginning from the Solow model they attempt to overcome its shortcoming - an exogenous steady path of economic growth - in a different approach and yet reach conclusions which have a common string. Romer studies the role of knowledge and new ideas for understanding long run economic growth, while Nordhaus focuses on understanding how the global economy and the global climate interact.

Romer presents an endogenous growth model by discussing how profit-oriented research-and-development in market economies can develop new technologies. He argues that ‘new ideas’ promote economic growth. ‘New ideas’, unlike other economic goods are non- rival and to varying extent excludable. ‘Ideas’ result in increasing returns to scale. ‘Ideas’ and market power go together and in the long run they give higher-than-marginal cost prices – monopoly profits. These monopoly profits encourage firms to undertake research and design. Further, because ‘ideas’ are non-rival in nature; they have the potential to cause positive spillover. Thus they have a positive externality. In an unregulated market the positive externality are unable to generate optimum outcomes and therefore an economic policy intervention can play an important role globally.

Nordhaus believes that the natural resources are a resource constraint due to their finiteness and focuses on the question of global warming and climate change. Nordhaus has added new dimensions to the Solow model by integrating into it the fundamental challenges the global economy was facing due to climate changes. According to him, these challenges are a result of a market economy's 'negative externalities' - increasing carbon concentration in the atmosphere caused by carbon emissions, increase in global caused by carbon concentrations in atmosphere via increased radiation, and he shows that economic and human welfare of the future generations needed policy interventions to resolve the issue.

Using Integrated Assessment Models (IAMs), and Dynamic Integrated Climate Economy (DICE) model he assesses the growth path of different economies, paying specific attention to carbon emissions and atmospheric carbon concentration level and its impact. He concludes that government intervention through various policies is essential in markets where negative externalities are prevalent. The key is to internalize the externalities that exist with policy measures.

The Nobel Committee has rightly noted, "Both Romer and Nordhaus emphasize that the market economy, while a powerful engine of human development, has important imperfections and their contributions have thus offered insights into how government policy could potentially enhance our long-run welfare."[1]

Romer's and Nordhaus's research opened up areas of further research on technological change and the climate-economy. Romer's work in 1980's initiated many studies and empirical analysis of growth trends across the globe. Subsequently he shifted his focus towards technological change and growth. He studied the role of knowledge, growth of human capital, technological adaptation on growth in the long run. Nordhaus's used the cost-benefit analysis study the climate changes and linked them with economic growth.

This research paper is a brief review of the contributions of Paul M. Romer and William D. Nordhaus. The paper is divided into six sections. Section 2 briefly discusses the Solow model. Section 3 explains Romer's endogenous growth model. Section 4 highlights the contributions of Norhdaus in combining growth and natural sciences mechanism into IAMS. Section 5 briefly compares the two thinkers and section 6 finally concludes.

The paper is based on secondary data. Various research papers/books published by both economists and critical reviews on their work has been studied extensively to interpret and explain their models.

2. The Solow Model

Solow presented a mathematical model to show how increased capital stock generates greater per capita production in his paper –"A Contribution to the Theory of Economic Growth" in 1956. The model shows that in the long run, all economies converge towards a steady equilibrium. Labour – augmenting technological progress in the long run which leads to improvements in production possibilities and the long run growth is exclusively determined by technological progress.

In Solow's model, in the long run the economy grows at a steady state because the investment curve has diminishing returns. As capital increases, production and investment increase but at a rate which is smaller as the capital stock is larger. A constant fraction of the capital stock depreciates steadily. Eventually, net investment falls to zero and the economy comes to rest in steady state. Thus, Solow concludes that in the short run, saving and investment stimulate growth, but diminishing returns to capital do not sustain long-run growth. Growth in the population and therefore in labor force results in growth of aggregate output over time, but this is not sustained growth.

An important conclusion from these implications was the "Convergence hypothesis" which stated that countries having the same technology, the same population growth rate and the propensity to save, but different initial capital-labor ratio, converge to the same growth rate in the long run. Poor countries grow relatively fast while the rich nations grow quite slowly and convergence occurs to the same growth rate in the long run.

In the early 1960s, many researchers began examining the Neoclassical model. Edmund Phelps (1961) and Jacques Desrousseaux (1961) posed the question of the best savings rate and presented the solution to this problem as the "Golden Rule" of growth. An important revision of the Solow model was the Cass-Koopmans optimal growth model.

The statistical data showed a decline in the growth rates in the United States and other developed countries in the late seventies and the Solow model was unable to explain the cause of this decline. Neither could the model explain the wide and persistent gap in per-capita income of developed and underdeveloped countries and the absence of absolute convergence in their growth rates as had been predicted by it.

Romer, in his seminal paper, "Increasing Returns and Long- Run Growth" (1986) in 'The Journal of Political Economy' presented his view that growth is 'endogenous' and can be achieved by elimination of the assumption of decreasing returns to capital.

3. Paul Romer: Growth Model of Endogenous Technological Change

> *"……an equilibrium model of endogenous technological change in which long-run growth is driven primarily by the accumulation of knowledge by forward-looking, profit-maximizing agents."*[2]

Data of average growth rates across 124 countries in the period of 1950-1980, did not agree with the Solow model.

[1] Economic Growth, Technological Change and Climate Change. Scientific Background on Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 2018 https://www.nobelprize.org/uploads/2018/10/advanced-economicsciencesprize2018.pdf

[2] Romer Paul M., 1986. "Increasing Returns and Long-Run Growth", Journal of Political Economy. Vol. 94, no.5 (October 1986): pp. 1002-1037.

There was a wide difference between the growth rates of output in these countries and Solow and Ramsey models failed to explain this and the cause of significant decline in productivity growth in the United States and other developed countries which began in late seventies. This was the starting point of Romer's theory.

In 1986, in his paper "Increasing Returns and Long-Run Growth" Romer presented an alternative model of economic growth in the long run to prove that long-run growth is driven primarily by the accumulation of knowledge.

The traditional growth theory takes into account only capital and labour as factors of production. Romer (1986) introduces 'knowledge' as a third input in the production function**.** In Romer's model technology is expressed through knowledge or 'ideas' which lead to steady and often an accelerating endogenous growth. Romer (1986) adds knowledge as a third input in the production function.

$Y=A(R)\,F(R_i, K_i, L_i)$ Where

Y = aggregate output

A = the public stock of knowledge from research and development R,

R_i = the stock of results from expenditure on research and development by firm i

K_i and L_i = capital stock and labor stock of firm respectively.

The production function is homogeneous of degree one in all its inputs R_i, K_i and L_i

The three key elements this Romer model are

i. 'Externalities'

ii. 'Increasing returns in the production of output'.

iii. 'Diminishing returns in the production of new knowledge'

Romer states that "…the key feature in the reversal of the standard results about growth is the assumption of increasing rather than decreasing marginal productivity of the intangible capital good knowledge."[3]

Romer assumes that human capital or the stock of knowledge of a business displays increasing marginal productivity and therefore the growth rate increases. Ideas give birth to new machinery or technology and improve returns to human capital. The research and development efforts of a firm lead to creation of knowledge. This investment in new knowledge leads to long run growth. Investment in new knowledge is motivated by the objective of profit maximization.

'Ideas' and Long Run Economic Growth

In his 1990 paper, Romer presented a model of Endogenous Technological Change wherein he puts forward his view that 'ideas' are more important than natural resources as they represent a new knowledge. New knowledge is used in the process of production in three ways – as a design to produce an intermediate input in an intermediate goods sector, as labor in final sector and as human capital and durable producer goods in the final product. Each new 'idea' increases the total stock of knowledge and thereby the productivity of human capital.

Ideas are Non Rival and Partially Excludable - An economic good is rival i.e. its use by one firm or person precludes its use by another. A purely nonrival good is a good whose use by one firm or person does not limit its use by another. An economic good is also excludable i.e. it is possible to 'exclude' consumers who have not paid for it from consuming it/ having access to it. It is impossible to exclude any individuals from consuming a public good. An economic good/private good is both rival and excludable and is brought and sold in a market.

Romer states that ideas are different because they are nonrival yet partially excludable. According to him, "The interesting case for growth theory is the set of goods that are nonrival yet excludable. … technology is a nonrival input. … technological change takes place because of the actions of self-interested individuals, so improvements in the technology must confer benefits that are at least partially excludable. … growth is driven fundamentally by the accumulation of a partially excludable, nonrival input."[4]

This is explained by Romer himself in the following box.

	Rival Goods	Non Rival Goods
100 ↑	Human Capital (for example, memorized commands for using software)	An encoded satellite television broadcast
Degree of Control or Excludability (Percent)	A floppy Disk	Computer code for a software application
		Operation manuals for Wal-Mart stores
0 ↓	Fish in Sea	Basic R &D
	Sterile Insects	

Source: Paul Romer, [5]

Ideas are non rival because ideas can be used as often as desired and in as many productive activities as desired. Ideas are partially excludable because the patent market is imperfect. The firm inventing a new idea can retain it through patents but only partially. Romer builds over these elemenst of non-rival, partial excludability of ideas and presents an endogenous long run model of economic growth.

New ideas translate into new products - A producer, motivated by private profit, incurs a cost in R&D cost and develops a 'variety' of products from new ideas and holding the patent right over production that 'variety' makes new knowledge/ideas created 'excludable'. This gives the firm a

[3] ibid

[4] Paul Romer, Endogenous Technological Change, *The Journal of Political Economy*, Vol. 98, No. 5, Part 2: The Problem of Development: AConference of the Institute for the Study of Free Enterprise Systems. (Oct., 1990), pp. S76

[5] Rival vs nonrival and excludable versus non excludable very simple. https://twitter.com/paulmromer/status/610978558626910210

'monopoly power' and gives birth to monopoly profits in the long run. This monopoly profit is an incentive which motivates private firms to engage in costly research and design activities and generate newer varieties. The initial cost of research and design is very high but in the long run as profits are generated the cost declines. Thus the firms have increasing returns to scale (as against constant returns to scale of Solow Model).

However, since the patent market is imperfect, the ideas are 'partially excludable'. The firm inventing a new idea can retain it through patents but only partially. An inventor/innovator can have effective 'monopoly power' over an idea by excluding others from using it only to the extent exclusive property rights can be enforced through patents, or intellectual property rights. Monopoly profits from knowledge creation cannot be sustained under perfect competition. In other words monopoly power allows private firms to earn monopoly profits from knowledge creation to the extent of excludability.

In the long run, ideas spread to other firms due to partial excludability and they also benefit from these new idea. The profits from investment in knowledge by one firm 'spillover' to the rivals firms also and benefit the entire society. Thus ideas generate 'positive externalities'.

Positive Externalities - Profits from investment by a firm in new technology are private benefits. These private benefits are only a part of the overall social benefits of an idea. The social benefits of ideas include the value of all positive externalities generated by beneficial spillovers to other firms or the society as a whole because new knowledge cannot be patented completely to keep the rivals in the economy from using it.

On the basis of these arguments it is concluded that on the one hand, some degree of monopoly power is essential to induce private agents to engage in costly research and design activities. On the other hand, any monopoly power also results in an efficiency loss. New ideas are an asset as they generate private profit. Patent rights are essential to ensure that the invention/innovation making firms make profits by excluding the rival firms through patents and copyrights, and other governmental safeguards. The limited private monopoly is necessary to ensure that new ideas keep taking birth but the spillover effects or positive externalities are also important. The society has to ensure the extent of these spillover effects generated. When more knowledge is created, the spillover effect becomes important. In this context, designing the optimal government policy is a challenging issue.

On the other hand where social benefits exceed the private profits, the firms must be given a subsidy. Therefore subsidies to foreign direct investments are essential to ensure that the spillover effects of new ideas reach the poor countries and their growth rate also improves.

Thus Romer concluded, "The most interesting positive implication of the model is that an economy with a larger total stock of human capital will experience faster growth. ….The model also suggests that low levels of human capital may help explain why growth is not observed in underdeveloped economies that are closed and why a less developed economy with a very large population can still benefit from economic integration with the rest of the world."[6]

4. William Nordhaus – "Integrating climate Change into long run economic analysis"

William Nordhaus is considered to be the representative of the mainstream in climate-change economics or the study of economic costs and benefits of climate change as well as the economic impact of policy measures taken to control global warming effects caused by emission of green house gasses (GHGs). Important published works of William Nordhaus focus on economic growth, the economics of climate change, social cost of economic growth. Nordhaus extended the Solow model and studied the long-run interactions between climate changes and socio-economic growth through the DICE and RICE models.

In the decade of 1970's, the interest of natural scientists began shifting to the question of global warming due to production of energy by the burning of fossil fuels and its negative impact on world climate. Nordhaus began to study the impact of global warming on both economic and human welfare. He asserted that the production processes across the world led to increase in atmospheric carbon concentrations which resulted in global warming and affected climate adversely, climate in turn affected the economy and results from the study of this action-reaction in natural sciences must be incorporated in a long run growth model.

Nordhaus focused on the spillover effects of growth or 'negative externalities' by including global warming caused by carbon emissions in his analysis. He developed a climate-economy model with three interlinked models:

1. A carbon-circulation model that maps emissions of fossil carbon to a path for atmospheric carbon-dioxide (CO2) concentration;
2. A climate model that describes the evolution of the climate over time depending on the path of CO2 concentration;
3. "An economic model that describes how the economy and the society are affected by climate change over time, and - closing the loop - how the path of economic activity leads to emissions of fossil carbon."[7]

Nordhaus combined these sub models into a single model – An Integrated Assessment Model (IAM) which can help in using a global economic model in making climate projections based on fossil-fuel emission.

The 1975/1977 IAMS Model was an important preliminary model developed by Nordhaus to show how to keep CO_2 concentration levels in the atmosphere and its impact within desirable limits at the lowest cost. In 1975, Nordhaus

[6] Paul Romer, Endogenous Technological Change, The Journal of Political Economy, Vol. 98, No. 5, Part 2: The Problem of Development: A Conference of the Institute for the Study of Free Enterprise Systems. (Oct., 1990) pp. S100

[7] Nobel Prize Organization, Popular Information: Integrating nature and Knowledge into Economics, The Prize in Economic Sciences, 218, The Royal Swedish Academy of Sciences.

constructed a model based on the findings of natural sciences on different carbon reservoirs and presented an annual linear model of carbon circulation to assess the evolution of atmospheric CO2 concentration in any emission scenario. He tried to analyse least cost measures to constraint atmospheric CO2 concentration.

DICE Model (1992) - *"an integrated model that incorporates the dynamics of emissions and economic impacts as well as the economic costs of policies to curb emissions."*[8]

In, 'The "DICE" Model: Background and Structure of a Dynamic Integrated Climate-Economy Model of the Economics of Global Warming' (1992), Nordhous, developed a mini model of climate change that, "…allows for different policies in the transition path from those in the ultimate steady state. It does this through the extension of the standard tools of modern optimal economic growth theory and adding to this analysis both a climate sector and a closed-loop interaction between the climate and the economy. The model is sufficiently small as to be transparent (or at least translucent), to allow a range of sensitive analyses, and to be available for a number of further extensions." [9] The model outlined the basic assumptions, parameters, variables and equations to analyze economic growth in the state of climate changes due to global warming. This was followed by his book, 'Managing the Global Commons: The Economics of Climate Change' in 1994.

The DICE model aims at estimation of an efficient growth path for the global economy which can ensure a balance between rate of capital accumulation and green house gas emissions or global warming effects on climate. The derivations of the DICE model for the global economy which has two sectors –the traditional economic sector and a climate sector. The model is based on the following assumptions-

- The global economy has an initial stock of capital and labor and a gradually improving technology.
- Population growth and technological change are exogenous factors
- Capital accumulation is determined by "optimizing the flow of consumption over time".
- Output is represented by the Cobb-Douglas production function in labour, capital and technology by competitive industries.

Nordhaus introduces the climate sector in the model by including equations related to GHGs/ CO_2 emission, carbon concentration, climate and damage relationship.

The Objective Function -

The problem faced by the economy is presented in the form of an objective function wherein the economy faces a problem of choice, "whether to consume goods and services, to invest in productive capital, or to slow climate change."

The objective function equation

$Max_{[c(t)]} \sum_{t=1}^{T} U[c(t), L(t)](1+\rho)^{-t}$ eq. 1

Where, U = flow of utility or social well-being

c(t) = flow of consumption per capita at time t

L(t) = level of population at time t

ρ = pure rate of social time preference = .03 percent per year

The maximization of the objective function is subject to economic constraints and climate- emissions constraints. Nordhaus uses the Ramsey Growth model to define the economic constraints.

A. Economic Constraints

The utility function is equal to the size of population [L(t)] multiplied by the utility per capita consumption level U[c(t)] and is represented as a power function in equation 2.

$U[c(t)] = L(t)\{[c(t)]^{1-\alpha} - 1\}/(1-\alpha)$ eq. 2

Where α = the rate of inequality aversion and is equal to zero

Output, Q(t) is given by equation 3, a constant-returns-to-scale Cobb-Douglas production function with capital K(t), labour proportional to population L(t)and technology A(t) inputs.

$Q(t) = \Omega(t)\, A(t) K(t)^{\gamma} L(t)^{1-\gamma}$ eq. 3

Where Q(t) = gross world product

Ω = output reduction due to emission controls and damages from climate change or climate impact.

A(t) = level of technology

K(t) = capital stock in period t

γ = The elasticity of output with respect to capital = .25

The capital and output data are historical data for the years 1960, 1965, 1970, 1975, 1980, 1985, and 1990. The model projects productivity growth.

Equation 4, shows the disposition of gross output Q(t) between consumption C(t) and gross investment I(t).

$Q(t) = C(t) + I(t)$ eq. 4

Per Capita Consumption is represented by equation 5-

$C(t) = C(t) / L(t)$ eq. 5

The capital balance equation represents the capital stock

$K(t) = (1-\delta_K)K(t-i)+I(t)$ eq. 6

Where δ_k = is the rate of depreciation of the capital stock which is taken to be .10 percent "which reflects an average lifetime of capital of ten years on a declining balance method."[10]

B. Climate-emissions-damage equations.

The second set of constraint equations, used by Nordhaus are related to impact of climate changes on the economy. He formulated equations for calculating gas emissions, carbon concentrations, and impact in the form of climate change, damages, and costs of regulating emissions.

Gas Emission Equation

The global economic activity is linked to GHG emissions by converting each green house gas into its CO_2 equivalent - E(t). The extent of global warming caused by each green

[8] Nordhaus, William D. An Optimal Transition Path for Controlling Greenhouse Gases, Science, New Series, Vol. 258, No. 5086 (Nov. 20, 1992), pp. 1315

[9] Nordhaus, William D. , , Cowles Foundation Discussion Paper No. 1009, Feb. 1992 The "DICE" Model: Background and Structure of a Dynamic Integratedd Climate-Economy Model of the Economics of Global Warming, pp. 3-4

[10] Ibid pp. 20

house gas over the indefinite future is called its total warming potential. Carbon dioxide has 80% of the total warming potential of the major GHGs.

A number of policy measures can be adopted to reduce the GHG emissions to control global warming. The rate of emission reduction achieved is called 'emission control rate' μ(t). "the control rate μ represents the fractional reduction of emissions relative to the uncontrolled emissions." [11] This emission control factor μ is endogenous and is zero during the historical period.

$E(t) = [1 - \mu(t)]\sigma(t)Q(t)$ eq. 7

According to Nordhaus, uncontrolled emissions decline exogenously primarily due to two reasons - one is the slow decline in use of coal as a fuel and the second is improvements in energy efficiency. Parameter σ (t) represents the uncontrolled ratio of GHG emissions to output and is an exogenous factor. Its exogenous decline, σ, is assumed to be 1.25 percent per annum. The values of σ (1965) = .519.Thus according to the model's calculations, g_σ = - 1.25percent per year.

Equation of Accumulation of GHGs in atmosphere -

$M(t) = \beta E(t) + (1+\delta M)M(t-1)$ eq.8

M(t) = CO2 Concentrations relative to preindustrial times

β = marginal atmospheric retention ratio and is estimated with the use of annual data on emissions and concentrations of CO2 = .64

δ_M = rate of transfer of GHGs from upper to lower reservoir. δ_M = .0833 per decade

$1/\delta_M$ = GHG turnover time (Nordhaus estimated this to be between 50 and 200 years for CO2)

M(1965) = 677 billion tons of carbon

C. The Climate Model - Nordhaus then proceeded to link accumulation of GHGs in atmosphere with the climate changes to study global warming. The objective was to understand the dynamics of impact of GHGs on climate. The DICE model developed equations to "parameterizes the overall relation between GHG concentrations and dynamics of climate change"[12].

Climate Model equation

$T(t) = T_1(t-1) + (1/R_1)\{F(t) - \lambda T(t-1) - (R_2/\tau_{12})[T(t-1) - T^*(t-1)]\}$ eq. 9

$T^*(t) = T^*(t-1) + (1/R_2)\{(R_2/\tau_{12})[T(t-1) - T^*(t-1)]\}$

T(t) = atmospheric temprature relative to the base period

$T^*(t)$ = temprature of deep oceans relative to the base period

$F_{(t)}$ = rate of radioactive forcing in the atmosphere from GHSs

R_1 = Thermal capacity of the upper stratum

R_2 = Thermal parameters of the deep ocean

τ_{12} = transfer rate from the lower to upper reservior

λ = climate feedback parameter

This equation is simplified climate model and Nordhaus attempts to find a numerical representation for it. Based on a study of Schlesinger and Jiang, Nordhaus calibrates the parameters of the DICE model.

Equation of relationship between global temprature increase and Income Loss – it measures the impact of climate change i.e damages due to global warming.

$d(t) = Q(t)\,\theta_1 T(t)^{\theta_2}$ eq. 10

where d(t) = Loss of global output due toglobal warming

θ_1 = Parameter representing the scale of damage = .00144

θ_2 = exponent representing the nonlinearity in the damage function =2

$d(t)/Q(t) = .013[T(t)/3]^2 = .00144\,T(t)^2$

This means that the world output declines by 1.3 percent due to damages caused by damages of global warminng caused by an average rise in temprature of 3 degree centigrade. Nordhas concluded in the model that, "Adjustments made for output composition in different countries raised the total impact to 1.3% of global output for all countries. In addition, there is evidence that the economic impact increases nonlinearly with climate change; the impact is here taken to be a quadratic function."[13]

The equation of estimated cost of reduction of GHGs

$TC(t)/Q(t) = b_1\,\mu(t)^{b2} = 0.0686\,\mu(t)^{2.887}$ eq. 11

Where TC(t) = total cost of reducing GHGs emissions

μ(t) = the rate of reduction of GHG emission

b_1 and b_2 = parameters of emmission-reduction cost function - .0686 and 2.887 respectively

The model estimated that the cost of reduction of GHGs by 5% was approximately 1% of the world output or $20 billion per year.

The Production Function – this is obtained by combining the cost and damage relationships (eq. 10) and cost reduction (eq.11)

$\Omega(t) = (1 - b_1\,\mu(t)^{b2}) / [1 + \theta_1 T(t)^{\theta 2}]$ eq. 12

The equations 1 to 12 form the DICE model which is optimized.

$\Omega(t) = = [1 - 0.0686\,\mu(t)^{2.887}] / [1 + 0.00144\,T(t)^2]$

After outlining the structure of the DICE model, Nordhaus proceeded to solve it. He used methods simplex method of linear programming, the quasi-Newton method and a projected Lagragean algorithm. The model was run on various versions of GAMs algorithms to calculate the impact of GHG on global output, consumption, savings, net return on capital, economic growth.

Finally the model assess the overall impact of measures adopted to control GHGs by estimating the cost of GHG controls and the comparing it with the benefits attempts to suggest an efficient strategy to deal with global warming.

D. The RICE Model

The Regional dynamic integrated model of Climate and the Economy (RICE Model), was developed and presented in Nordhaus and Yang 1996. The data for RICE-99 were collected for thirteen sub-regions, which were then aggregated into eight regions for modeling purposes. The RICE model is a

[11] Ibid pp.10

[12] Nordhaus, William D. An Optimal Transition Path for Controlling Greenhouse Gases, Science, New Series, Vol. 258, No. 5086 (Nov. 20, 1992), pp. 1316

[13] Ibid, pp 1316

"three-factor production function in capital, labor, and carbon-energy... develops an innovative technique for representing the demand for carbon fuels and uses existing energy-demand studies for calibration…The new RICE model changes the treatment of energy supply to incorporate the exhaustion of fossil fuels."[14]

The RICE model treats the supply of fossil fuel as an explicit factor and considers it as limited and exhaustible due to which the fuel prices rise continuously.

E. Policy Measures for controlling Global Warming

The society faces a trade –off between present and future consumption. The adoption of policies to control emission of GHGs to control global warming in the future necessitates 'climate-investment' which implies reduction in productive investment, output and consumption today. The greater is the reduction in 'damages' by reducing use of fossil-fuel, higher is the consumption in the future. The climate investments have a positive impact on agricultural output, coastlines, and the global. Therefore, the Nations must adopt policy measures of which decrease the quantity of negative capital (concentrations of GHGs) and prevent economically harmful climate change. Each region's "social welfare function" determines choices about the path for consumption and investment.

Policymakers can use measures like carbon taxes or emissions permits for achieving an economically efficient level of emissions for each region equal to the global environmental shadow price of carbon. "The environmental shadow price of carbon is the impact through environmental channels of a unit of emissions today on the present value of consumption in all regions in all future periods"[15] . The IAMs model calculates the shadow price of carbon emissions. In an optimized climate policy the social cost of carbon is equal to the carbon tax. Estimates of the SCC help the policymakers to develop economically efficient policies related to climate-affecting decisions like carbon tax, subsidies for use of low-carbon energy sources, regulations on energy efficiency in motor vehicles and for power plants.

Alternative policies analyzed in RICE-99 and DICE-99 models

1.	No controls (baseline). No policies taken to slow greenhouse warming.
2.	Optimal policy. Emissions and carbon prices set at Pareto optimal levels.
3.	Ten-year delay of optimal policy. Delays optimal policy for ten years.
4.	Stabilize emissions of high-income regions (Kyoto Protocol). Annex I regions reduce their emissions 5 percent below 1990 levels forever, with trading allowed among Annex I regions.
5.	Stabilizing global emissions. Stabilizes global emissions at 1990 levels.
6.	Concentrations stabilization. Stabilizes concentrations at two times preindustrial levels.
7.	Climate stabilization. Sets policies to limit temperature rise to (a) 2.5° C or (b) 1.5° C. 8.
8.	Geoengineering. Implements a geoengineering option that offsets greenhouse warming at no cost.

Source - William D. Nordhaus and Joseph Boyer, Warming the World: Economic Models of Global Warming. MIT Press, Cambridge Mass., 2000, pp122

The countries adopt optimal policies to maximise the value of the economic welfare represented in equation 1 subject to all economic and climate constraints by levying carbon taxes, imposing reguations to reduce GHG emissions. These are being adopted since 1990. A carbon tax is imposed on products which produce GHGs. It attempts to induce the producers to substitute use of fossil fuel or GHG – itensive inputs by raising the cost of of fosssil fuels. Nordhaus estimated that the optimal carbon tax for the period of 1990-99 would be $5 per ton of .

Geo-engineering is technological policy, a "large-scale engineering to offset the warming effect of greenhouse gases. Such options include injecting particles into the atmosphere to increase the backscattering of sunlight and stimulating absorption of carbon in the oceans."[16] Geo-engineering is a comparatively low cost strategy however the ecologists and environmentalists have insufficient knowledge regarding its possible environmental impact. Nourdhaus defined four efficiency standards for designing economically efficient policies –

i. How-efficiency - ways of achieving emissions reductions in a given year and region by domestic auctioning of emissions permits or via carbon taxes.

ii. Where-efficiency – allocation of emissions reductions across regions to minimize the costs of attaining the global emissions target for a given year.

iii. When-efficiency - efficient allocation of emissions over time.

iv. Why-efficiency - attaining the ultimate objective of a program - a set of policies that balances the costs of abatement and benefits of damage reduction. The optimal program in policy 2 satisfies why-efficiency.

Nordhaus' extended his study to understand and quantify the uncertainties inherent in climate change. He stated that**,** "there is substantial uncertainty about the path of climate change and its impacts. The ranges of uncertainty for future emissions, concentrations, temperature, and damages are extremely large."[17] In 2017, Nordhaus provided an analysis, for five key uncertain parameters: (i) the coeffcient on squared temperature in the damage function, (ii) the growth rate of aggregate productivity, (iii) the speed at which the economy decarbonizes through technical change, (iv) the climate sensitivity, and (v) the capacity of the intermediate carbon reservoir M^U to store carbon.

[14] William D. Nordhaus and Joseph Boyer, Warming the World: Economic Models of Global Warming. MIT Press, Cambridge Mass., 2000, pp 6

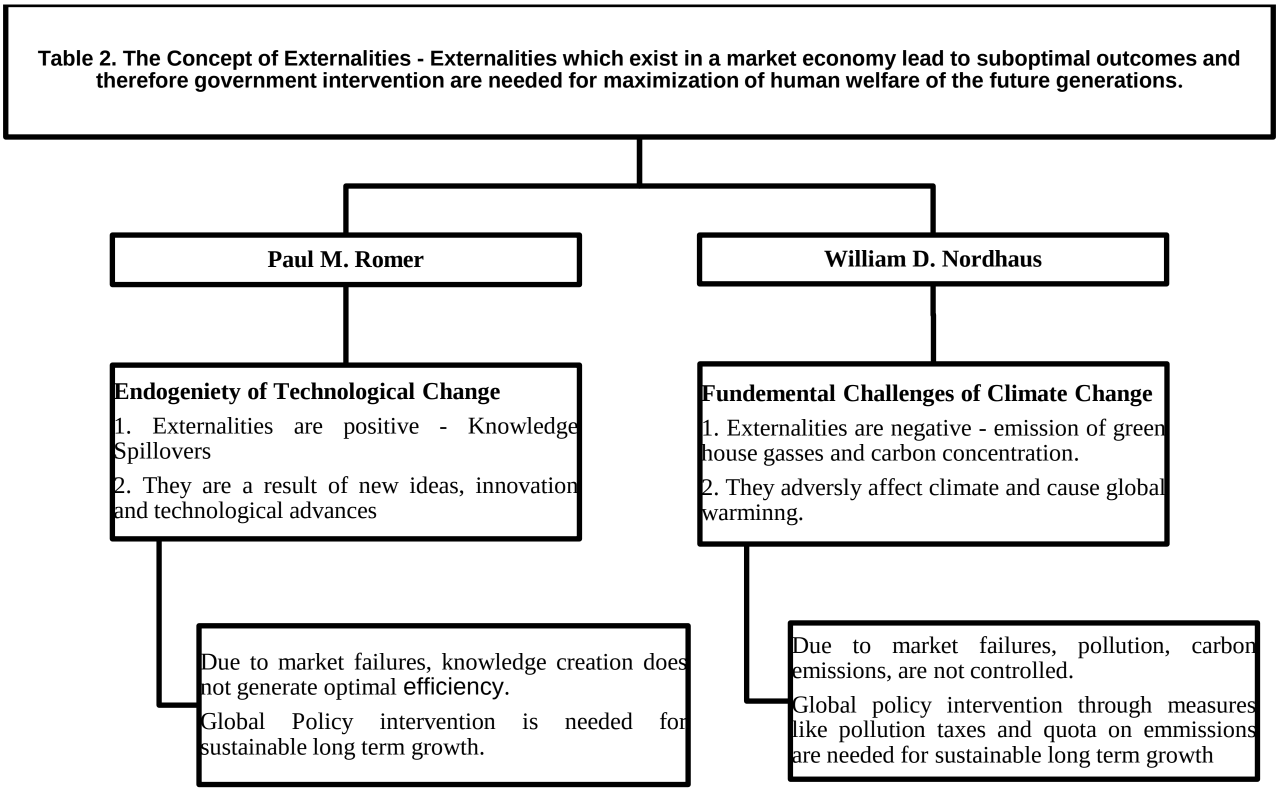
[15] William D. Nordhaus and Joseph Boyer, Warming the World: Economic Models of Global Warming. MIT Press, Cambridge Mass., 2000, pp27

[16] William D. Nordhaus and Joseph Boyer, Warming the World: Economic Models of Global Warming. MIT Press, Cambridge Mass., 2000, pp 126

[17] William Nordhaus, Projections and Uncertainties about Climate Change in an Era of Minimal Climate Policies, American Economic Journal: Economic Policy 2018, 10(3): 333–360

The DICE/RICE models attempt to make reliable predictions by solving the model for each uncertain parameter combination. This helps in assessing the robustness of the model's key predictions in different dimensions.

6. Paul Romer and William Nordhaus – A brief comparative analysis -



The next chart has summed up the key facts of the contributions of both the laureates to show how despite being different in their approach, both have a common string.

Endogenous Growth Theory	Combining Growth and Climate Change into integrated assessment model.
1. Ideas are crucial for Growth	1. Global Growth obstacles a. Finiteness of natural resources b. Climate Change
2. Pre-Conditions of Ideas – Non- Rival and Excludable	2. GHGs, Carbon concentration, global warming due to economic activity.
3. Ideas Increase Returns to Scale	3. Result is negative impact on human welfare. 'NegativeCapital'
4. Ideas and Market Power go hand in hand	4. IAMS – DICE model/RICE model to assess the economic growth path and the impact on climate i.e. economic damage.
5. Monopoly Profit is the engine of market R&D	5. Cost-Benefit analysis of growth and climate change.
6. Positive Spillover effects/Externalities –Non-rivalness	6. Negative Spillovers/ Externalities - damages and uncertainties
Conclusion – Unregulated Markets produce technological changes inefficiently therefore government intervention plays an important role Adaptation through technological change and formulation of policy in redirecting technological change is needed.	Conclusion – Market economy generates inefficient future outcomes at global level in the form of climate change. These must be controlled through government intervention – policy measures like carbon taxation, emission permits.

Conclusion

The above study has extensively analysed the contributions of Paul M. Romer and William D. in long-run development. Both initiated their study from the neoclassical growth model, and introduced in it a new driver of long-run economic growth ('ideas' and climate). Both emphasized externalities in their analysis and suugested policy measures for sustainable long run growth. Starting form a common point, they used a different path yet focused on global economic welfare of the coming generation. The nobel prize organization has rightly stated that both the laureates have "been fundamental in allowing current and future researchers to improve our understanding of the best way to progress towards sustained and sustainable global economic growth."[18]

[18] Nobel Prize Organization, Popular Information: Integrating nature and Knowledge into Economics, The Prize in Economic Sciences, 2018, pp. 7

References

1. Martens, Bertin, The Cognitive Mechanics of Economic Development and Institutional Change,Rouledge,2004 https://books.google.co.in/books?id=u4F_AgAAQBAJ&dq=ideas+are+non+rivaland+partially+excludable
2. Mishra, Dr. Satyabrata, The New Theory of Economic Growth: Endogenous Growth Model, International Journal of Business and Management Invention, Volume 5 Issue 9 September. 2016, PP—50-53, www.ijbmi.org
3. Nobel Prize Organization, The Solow Growth Model, Press Release, https://www.nobelprize.org/prizes/economic-sciences/1987/press-release/ [accessed 22/11/2018]
4. Nobel Prize Organization, Popular Information: Integrating nature and Knowledge into Economics, The Prize in Economic Sciences, 2018, https://www.nobelprize.org/uploads/2018/10/popular-economicsciencesprize2018.pdf [accessed 22/11/2018]
5. Nobel Prize Organization, Economic Growth, Technological Change, and Climate Change,https://www.nobelprize.org/uploads/2018/10/advancedeconomicsciencesprize2018.pdf2018, [accessed 22/11/2018]
6. Nordhaus, William D. An Optimal Transition Path for Controlling Greenhouse Gases, Science, New Series, Vol. 258, No. 5086 (Nov. 20, 1992), pp. 1315-1319 https://www.jstor.org/stable/2880417 [Accessed: 25-02-2019]
7. Nordhaus, William D. , The “DICE” Model: Background and Structure of a Dynamic Integratedd Climate-Economy Model of the Economics of Global Warming , Cowles Foundation Discussion Paper No. 1009, Cowles Foundation for Research in Economics at Yale University, February, 1992 http://cowles.yale.edu/sites/default/files/files/pub/d10/d1009.pdf
8. Nordhaus, William D., Joseph Boyer, Warming the World: Economic Models of Global Warming. MIT Press, Cambridge Mass., 2000; https://eml.berkeley.edu/~saez/course131/Warm-World00.pdf [accessed on 5/3/2019]
9. Nordhaus, William, D, Geography and macroeconomics: New data and new findings, PNAS March 7, 2006 103, https://www.pnas.org/content/103/10/3510 [accessed on 24/2/2019]
10. Nordhaus, William D., Projections and Uncertainties about Climate Change in an Era of Minimal Climate Policies, American Economic Journal: Economic Policy 2018, 10(3): 333–360, https://doi.org/10.1257/pol.20170046
11. Nuzzo, Regina, Profile of William D. Nordhaus, PNAS, June 27, 2006, vol. 103, no. 26
12. Romer Paul M., “Increasing Returns and Long-Run Growth", Journal of Political Economy. Vol. 94, no.5 (October 1986): pp. 1002-1037. [Accessed on 28/11/2018]
13. Romer, Paul M. , Growth Based on Increasing Returns Due to Specialization, The American Economic Review, Vol. 77, No. 2, Papers and Proceedings of the Ninety- Ninth Annual Meeting of the American Economic Association (May, 1987), pp. 56-62 Published by: American Economic Association Stable URL: http://www.jstor.org/stable/1805429
14. Romer, Paul M., 1990, Endogenous Technological Change, The Journal of Political Economy, Vol. 98, No. 5, Part 2: The Problem of Development: A Conference of the Institute for the Study of Free Enterprise Systems. (Oct., 1990), pp. S71-S102.
15. http://links.jstor.org/sici?sici=00223808%28199010%2998%3A5%3CS71%3AETC%3E2.0.CO%3B2-8
16. Romer, Paul M. , 1994, The Origins of Endogenous Growth, Journal of Economic Perspectives—Volume 8, Number 1—Winter 1994–Pages 3–22, https://www.jstor.org/stable/2138148
17. Paul Romer, Rival vs nonrival and excludable versus non excludable very simple. https://twitter.com/paulmromer/status/610978558626910210 [accessed on 14/2/2019]
18. Solow, Robert, M ., A Contribution to the Theory of Economic Growth, The Quarterly Journal of Economics, Vol. 70, No. 1 Feb., 1956, pp. 65-94, The MIT Press Stable. http://www.jstor.org/stable/1884513,http://piketty.pse.ens.fr/files/Solow1956.pdf [accessed on 22/11/2018]
19. Summers R and A Heston, Improved International Comparison of Real product and its composition: 1950-1980, Review of Income and Wealth, Vol.3, Issue 2, 1982, http://www.roiw.org/1984/207.pdf [accessed on 9/2/2019]
20. The Neoclassical Growth Model, The Convergence Hypothesis, https://cruel.org/econthought/essays/growth/neoclass/solowconv.html
21. https://www.nobelprize.org/prizes/economic-sciences/1987/press-release/ [accessed on 22/11/2018]