International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 13 Issue 8 ǁ August 2025 ǁ PP. 24-29

Stochastic Optimization of Renewable Energy Alternatives for Power Generation in Nigeria Using Markov Chain Modeling

Tachere, O.Z[1*] and Eme, L.C [2].
[1]*Civil and Water Resources Department, Delta State University State Technology, Ozoro, Nigeria*
[2]*Civil Engineering Department, Chukwuemeka Odumegwu Ojukwu, University, Uli*

Abstract
Nigeria's overdependence on fossil fuels has led to myriads of problems involving energy insecurity, environmental degradation, and economic instability. This study addresses the urgent need to transit to sustainable energy systems by evaluating and optimizing various alternative renewable energy sources using a finite method of Markov Chain. The method adopted was forecasting the population of Nigeria based on the 2006 census and a 3% annual growth rate over 50 years was used to estimate future energy demands. Seven renewable energy sources including solar power, hydropower, biomass power, biomass gasifier, wind turbines, tidal turbines, and flywheel water turbines were analyzed in terms of cost-effectiveness and net benefits using Bill of Engineering Measurement and Evaluation (BEME). A benefit-versus-purpose model was developed, and Markov chain analysis was applied to determine the optimal energy alternative based on transition probabilities and revenue functions. Results indicate that flywheel turbine technology offers the highest net benefit (₦526.8 trillion) and long-term efficiency, making it the most viable option economically to the tune of ₦4445.12 trillion (after the seventh iteration) for mitigating Nigeria's energy crisis. This study demonstrates how stochastic modeling guides energy policy and infrastructural planning, giving a pathway toward sustainable environmental friendly, reliable, and economically beneficial power generation.
Keywords: *Renewable Energy, Markov Chain, Energy Optimization, Flywheel Turbine, BEME*

Date of Submission: 27-07-2025 Date of acceptance: 05-08-2025

I. Introduction

There has been a global shift toward sustainable energy development in recent years in response to growing concerns about environmental impacts of fossil fuels and the depletion of non-renewable resources. Different countries globally are investing into renewable energy technologies to address matters related to climate change, energy security and economic development. Nigeria, in particular is faced with a unique energy crisis characterized by insufficient electricity supply, with excess reliance on fossil fuels, and underutilization of its abundant renewable energy potential. Despite its substantial reserves of renewable resource like solar, wind, hydro, and biomass, Nigeria continues to experience the occurrence of power outages and limited access to electricity, especially in rural areas. The nation's current energy infrastructure is strongly dependent on oil and gas, which are not only environmentally damaging but also economically volatile due to irregular global prices. This study is aimed at establishing a most cost-effective and sustainable renewable energy source for Nigeria using Markov chain analysis. This study proposes the use of Markov Chain modeling as a decision tool to evaluate and optimize renewable energy alternatives in Nigeria. It analyzes transition probabilities between different energy states over a period of time, the model forecasts the most economically and environmentally possible renewable energy option based on future energy demand. It incorporates both cost analysis and projected population growth, this approach aims to provide a scientifically sound framework for overall energy planning and policy formulation in Nigeria.

The dependence on oil-based fuels is speedily increasing leading to unsustainability, prompting global researchers into alternative energy sources. For instance, Mikael and Kjel (2010) examined the conversion of coal to liquid fuel (CTL) in South Africa being a strategy to alleviate energy shortages. Similarly, Samuel and Xiaobo (2007) highlighted global energy challenges and emphasizes on the importance of renewable energy technologies such as solar electricity generation, hydrogen fuel production, and fuel cell applications. Musa, et al (2022), developed equations using Markov chain process to derive steady state expressions to validate the model on varying failure and repair rate of solar pumping system providing insight for maintenance manager through optimized maintenance strategies from first order ordinary differential. Also Ibrahim and Canan (2005) examined environmental challenges and socio-economic to energy problems, making clear that solar photovoltaic systems as cost-effective, durable and an alternative to fossil fuels. Markov chain models have been employed to optimize water resource projects related to energy. For instance, Eme and Ohaji (2019) used Markov chains to enhance dam project efficiency for flood control, irrigation, tourism and hydropower. Eme et al. (2019) further worked on the usefulness of harnessing streams and marine currents for hydrokinetic renewable energy systems. In addition, Eme (2015) employ finite Markov chain to model the Anambra and Imo River Basins with focus on hydropower generation irrigation and water supply, aiming to improve employment and social welfare while mitigating climate and energy crises. In another related study, Eme (2019) used the finite Markov chain approach for optimizing conjunctive water resource management in the Anambra-Imo River Basin in order to maximize benefits of irrigation, hydroelectric power among others. Nkemnole and Akinola (2020) emphasized on the power sector in Nigeria facing earnest shortage of power causing energy demand fluctuation, deregulation with constrains on economic development. They used Harvey, Autogressive and Markov chain to compare these three result showing that Markov model was the optimal model for electricity generation and consumption. Agada et al (2023), utilized modeling of wind speed and developing a monthly Markov chain using the Beaufort scale in the sixteen states of northern Nigeria. They suggest that the proposed stochastic framework can be effectively applied to guide wind-farm site and wind-turbine design. More so Fioriti & Parzen (2022) used Macro energy system models as a technical decision maker to support policies steering up sustainable, affordable, and reliable future for the global energy state.

Biomass energy has also gained attention hence Munir et al. (2017) emphasize on the extensive use of agricultural and animal waste biomass for cooking and heating in Turkey, while Kevin and Ahmed (2019) worked on biomass conversion into bioenergy as a viable solution to energy challenges. Naveen and Thippeswarry (2016) identified bioethanol production from Areca nut husk as a sustainable waste management and renewable fuel solution. Aravind et al. (2020) utilized green algae as a feedstock for bioenergy production, including bio-oil, bio-char, and biogas. Renewable energy technologies have been applied in local contexts as well hence Elias et al. (2021) assessed the cost-effectiveness of bioenergy, from his finding, they said it more economical than conventional sources, especially for agro-industrial uses. John et al. (2019) also worked on Miscanthus grass for bioenergy applications as a solution to energy crises. Eboibi and Edje (2018) explored the potential of microalgae as a renewable feedstock for liquid fuel production via hydrothermal liquefaction (HTL) by developing a predictive models to mitigate climate change, reduce pollution, and address energy deficits. These researchers focused on bioenergy as a means of eradicating energy crises.

Eme and Tachere (2023) designed different energy sources using hydropower, wind turbines, biogas, and solar systems for communities in Ogor Kingdom, Delta State, using a Bayesian decision model to evaluate the economic viability of these alternatives to unreliable grid supply. Collectively, these studies emphasizes on the urgent global need for renewable energy driven by diminishing fossil fuel reserves, population growth, and the imperative for sustainable energy security. Unlike previous studies focusing on individual technologies, this research work utilizes a stochastic model to evaluate several renewable sources simultaneously.

II. Materials and Methods

To estimate the energy demand for the renewable sources, a population forecast of the study area was conducted using the 2006 population census data, as published by the National Bureau of Statistics (2020). The projection used the Compound Interest formula, being a widely accepted method in engineering for forecasting future values particularly those that are relevant for planning infrastructure with long-term usage. The formula in Equation 1 was used.

$F = P\left(1 + \frac{r}{100}\right)^{n}$, where 1

- F = future population
- P = present population
- r = annual growth rate (%)
- n = number of years projected into the future

A growth rate of 3% was assumed over a 50-year period for the projection.

Subsequently, seven green energy technologies were designed for the study area, they include solar power, hydropower, biomass gasifier, biomass power, tidal turbine, wind turbine, and flywheel water turbine. For each technology, a Bill of Engineering Measurement and Evaluation (BEME) was prepared, from which a benefit-purpose matrix was developed to evaluate their specific contributions. To assess the long-term economic viability and optimize energy resource deployment, the finite Markov chain method was applied. This stochastic modeling approach enabled the construction of an econometric framework to simulate future scenarios and determine the most efficient and beneficial mix of renewable energy technologies for sustainable development within the river basin region.

2.1 Finite Method of Markov Chain concept.

If a gardener plans to retire after N years, the objective is to determine the optimal decision for each year specifically, whether to fertilize or not. The primary goal is to maximize the expected cumulative revenue over the N year period. Let k = 1 and k = 2 denote the two possible decisions available to the gardener. The matrices P and R represent the transition probabilities and the corresponding revenue functions associated with each decision, respectively. This scenario can be modeled as a finite-stage dynamic programming (DP) problem. To generalize, let the number of possible states at each stage (year) be m. The finite stage DP was chosen because it is a strong tool which does not depend on past history but relies on the using the best course of action of the present scenario to determine the optimal policy of the maximum expected revenue.

III. Results and Discussion

Table 1 shows the results of the various benefits associated with each renewable energy source. The seven renewable energy sources were modeled, and their cost-effectiveness was evaluated by calculating the net benefits as the difference between gross benefits and the total cost of each scheme. These net benefits formed the basis for applying the Markov chain analysis. Subsequently, the infinite-horizon Markov chain method was employed to analyze the alternative renewable energy options.

Table 1: Benefit versus Purpose (Tr)

Energy sources	Objectives (Trillions)						
Solar power	48.5	38.4	40.2	43.6	26.8	39	16.1
Hydropower	34.2	46.6	28.4	72.7	37.6	46.7	69
Biomass power	36.2	31.4	26	71.2	17.6	33	17.3
Biomass gasifier	9.8	21.3	22.2	19.2	27.7	10.8	26
Wind turbine	39	32.2	68	45.2	50.7	38.9	70.6
Tidal turbine	38.1	28.7	121.4	45.7	51.1	31	69
Flywheel Turbine	42.2	55.9	122.1	125.9	82	54.4	44.3

Table 2 shows the calculation of the derived BEME on Benefit versus Purpose of the alternative renewable energy sources. (R_2 Net Benefit).

Table 2: Net Benefits to the alternative energy sources capital projects under various Objectives

Energy sources	Objectives (Trillion)							∑
Solar power	48.5	38.4	40.2	43.6	26.8	39	16.1	252.6
Hydropower	34.2	46.6	28.4	72.7	37.6	46.7	69	335.2
Biomass power	36.2	31.4	26	71.2	17.6	33	17.3	232.7
Biomass gasifier	9.8	21.3	22.2	19.2	27.7	10.8	26	137
Wind turbine	39	32.2	68	45.2	50.7	38.9	70.6	344.6
Tidal turbine	38.1	28.7	121.4	45.7	51.1	31	69	385
Flywheel Turbine	42.2	55.9	122.1	125.9	82	54.4	44.3	526.8
∑	248	254.5	428.3	423.5	293.5	253.8	312.3	2213.9

Discussion of Table 2

i. Table 3.2 shows the calculation gotten from the Bill of Engineering Measurement and Evaluation (BEME). This is the Benefit versus purpose of the renewable energy projects. The Net Benefit was gotten from deducting the cost from Gross.

ii. The highest value from the benefit with maintenance was N125.9Tr gotten from flywheel renewable energy

iii. The flywheel technology is cheaper when compared to other technologies because it is simple and yields maximum benefits since it uses the principle of hydrokinetic (fluid flow velocity which is a great potential excellently produced in Nigerian rivers.

The interval scale as presented in this study using the soil condition is between 1 – 7. The transition probability matrix P^1 reflects the assumption that the current year's productivity cannot exceed that of the previous year. According to the Markov decision framework, the gardener conducts a chemical test each season to evaluate soil conditions. Based on the test results, productivity for the upcoming season is categorized into one of seven possible states: (i) Excellent, (ii) Very Good, (iii) Good, (iv) Fair, (v) Weak, (vi) Poor, and (vii) Very Poor. This framework highlights the Markov property, where the productivity outcome for the current year depends solely on the soil condition of the preceding year which is independent of any earlier states. The Markov chain, therefore, provides a mathematical model for representing such stochastic processes, where the next state of the system is determined only by its present state.

$P^1 \times R^1$

P^1 =

0.09	0.16	0.13	0.10	0.18	0.14	0.20
0	0.18	0.23	0.11	0.13	0.21	0.14
0	0	0.18	0.10	0.34	0.12	0.26
0	0	0	0.31	0.13	0.36	0.20
0	0	0	0	0.32	0.41	0.27
0	0	0	0	0	0.58	0.42
0	0	0	0	0	0	1.0

R^1 =

53.35	41.8	44.22	47.97	29.48	42.9	17.71
37.62	51.26	31.24	79.97	41.36	51.37	75.9
39.82	34.54	28.6	78.32	36.3	36.3	19.03
10.78	23.43	24.42	21.12	30.47	11.88	28.6
42.9	35.42	74.8	49.72	55.77	42.78	27.66
41.91	31.57	133.54	50.27	56.21	34.1	75.9
46.42	61.49	134.31	134.49	90.2	59.84	48.73

P^2 =

0.19	0.15	0.16	0.17	0.11	0.15	0.07
0.10	0.14	0.08	0.22	0.11	0.14	0.21
0.16	0.13	0.11	0.31	0.08	0.14	0.07
0.07	0.16	0.16	0.14	0.20	0.08	0.19
0.11	0.09	0.20	0.13	0.15	0.11	0.21
0.10	0.07	0.32	0.12	0.13	0.08	0.18
0.08	0.11	0.23	0.24	0.16	0.10	0.08

R^2 =

48.5	38.4	40.2	43.6	26.8	39	16.1
34.2	46.6	28.4	72.7	37.6	46.7	69
36.2	31.4	26	71.2	17.6	33	17.3
9.8	21.3	22.2	19.2	27.7	10.8	26
39	32.2	68	45.2	50.7	38.9	70.6
38.1	28.7	121.4	45.7	51.1	31	69
42.2	55.9	122.1	125.9	82	54.4	44.3

Table 3: Summary of Computation of V_1^1 and V_1^2 used in stage 6 to 1

S/No	V_1^1	V_1^2
1	36.89	38.74
2	52	43.72
3	34.63	42.05
4	20.51	21.68
5	48.86	53.38
6	55.45	71.7
7	48.73	89.93

A multiple of P^1 by R^1 and P^2 by R^2 were multiplied to get the table above. A series of iterations from the transition matrices gave the final presentation in Table 4.

Table 4: Stage 1 Computation

$V_i^k + P_1^k F_5^{(1)} + P_{12}^k F_5^{(2)} + P_{13}^k F_5^{(3)} + P_{14}^k F_5^{(4)} + P_{15}^k F_5^{(5)} + P_{16}^k F_6^{(6)} + P_{17}^k F_7^{(7)}$				Optional solution
i	K = 1	K = 2	$F_1^{(i)}$	K *
1	1876.83+(0.09×1876.83)+(0.16×1891..41)+(0.13 × 1949.17)+(0.10× 1879.03)+(0.18×2019.07+(0.14x 2019.34)+(0.20x 2222.56)=3879.9	1815.16+(0.19×1876.83)+(0.15×1891.41)+(0.16×194 9.17)+(0.17×1879.03)+(0.11×2019.07)+(0.15x 2019.34)+(0.07x 2222.56) = 3711.04	3879.9	1
2	1891.14+(0×1876.83)+(0.18×1891..41)+(0.23×194 9.17)+(0.11×1879.03) + (0.13×2019.07) + (0.21 x 2019.34) + (0.14x 2222.56) =3884.3	1886.25 + (0.10×1876.83) + (0.14×1891.41) + (0.08×1949.17) + (0.22×1879.03) + (0.11×2019.07) + (0.14 x 2019.34) + (0.21x 2222.56) =3879.6	3884.3	1
3	1949.17+(0 ×1876.83)+ (0×1891..41)+(0.18×1949.17)+(0.10×1879.03)+(0. 34×2019.07)+(0.12x 2019.34) + (0.26x 2222.56) =3990.6	1797.69+(0.16×1876.83)+(0.13×1891.41)+(0.11×194 9.17) + (0.31×1879.03) + (0.08×2019.07) + (0.14 x 2019.34) + (0.07x 2222.56) = 3740.6	3990.6	1
4	1879.03 + (0×1876.83) + (0×1891..41) + (0×1949.17) + (0.31×1879.03) + (0.13×2019.07) + (0.36 x 2019.34) + (0.20x 2222.56) = 3895.5	1867.05+(0.07×1876.83)+(0.16×1891.41) + (0.16×1949.17) + (0.14×1879.03) + (0.20×2019.07) + (0.08 x 2019.34) + (0.19x 2222.56) = 3863.6	3895.5	1
5	2019.07 + (0×1876.83) + (0×1891..41) + (0×1949.17) + (0×1879.03) + (0.32×2019.07) + (0.41 x 2019.34) + (0.27x 2222.56) = 4093.2	1901.73 + (0.11×1876.83) + (0.09×1891..41) + (0.20×1949.17) + (0.13×1879.03) + (0.15×2019.07) + (0.11 x 2019.34) + (0.21x 2222.56) =3904.24	4093.2	1
6	2019.34+ (0×1876.83) + (0×1891..41) + (0×1949.17) + (0×1879.03) + (0×2019.07) + (0.58 x 2019.34) + (0.42x 2222.56) = 4124.03	1901.54 + (0.10×1876.83) + (0.07×1891..41) + (0.32×1949.17) + (0.12×1879.03) + (0.13×2019.07) + (0.08 x 2019.34+ (0.18x 2222.56) = 3894.9	4124.03	1
7	2222.56 + (0×1876.83) + (0×1891..41) + (0×1949.17) + (0×1879.03) + (0×2019.07) + (0 x 2019.34) + (1x 2222.56) =4445.12	1870.03 + (0.08×1876.83) + (0.11×1891..41) + (0.23×1949.17) + (0.24×1879.03) + (0.16×2019.07) + (0.10 x 2019.34) + (0.08x 2222.56) =3830.3	4445.12	1

Discussion of results on Table 4

i. Table 4 show the computation at stage five with K = 1 having a maximum value of 4445.12 Trillion
ii. While K = 2 having a maximum value of 3904.24
iii. The $F_1^{(i)}$ value from 8308.9 to 9485.2 with the optimal solution K as 1, 1, 1, 1, 1, 1, and 1
iv. This clearly shows that the use of flywheel and other renewable energy sources will boost the nation's Gross Domestic Product and resolve the energy crises in Nigeria.

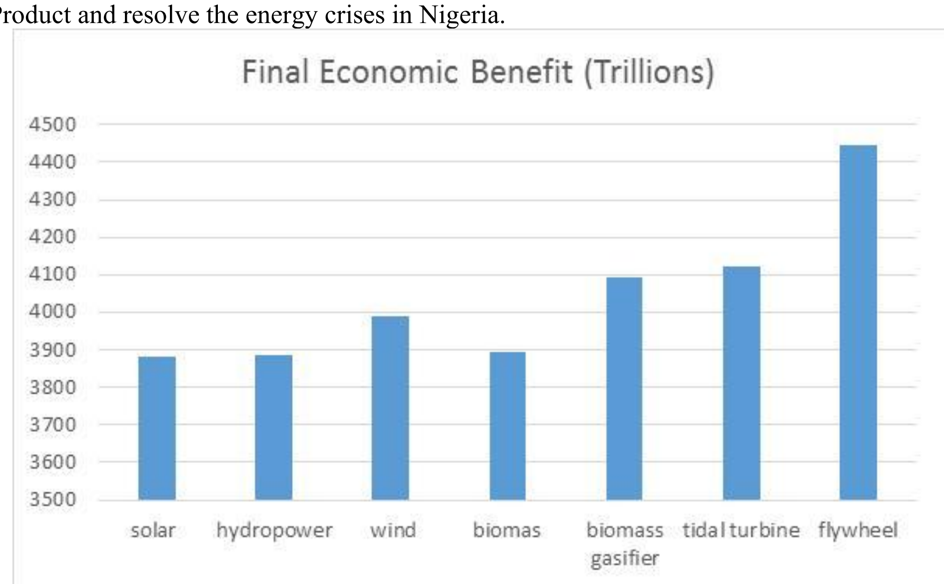

Figure 1 Final economic benefit and the various sources of energy

The figure above shows the economic benefits of the seven sources of energy signifying that flywheel water turbine yielded the maximum economic benefit.

IV. Conclusion

This study demonstrated the applicability of the Markov chain modeling approach in optimizing renewable energy alternatives for sustainable power generation in Nigeria by integrating econometric analysis and transition probability models, the study effectively evaluated seven renewable energy sources which are solar, hydropower, wind, biomass, biomass gasifier, tidal turbine, and flywheel water turbine based on their cost-effectiveness and net benefits. Using a population forecast as a baseline for energy demand over a 50-year horizon presenting flywheel turbine as the best performed having an economic benefit of N4.45 Quadrillion. The findings indicate that strategic deployment of renewable resources, guided by stochastic optimization techniques, can significantly improve energy reliability and economic outcomes in the studied regions.

Reference

[1]. Agada, M. E., Sadiq, A. S., & Ibrahim, I. (2023). *Comparative analysis of renewable energy integration in sub-Saharan Africa using stochastic models*. Journal of Renewable Energy Research, 15(2), 110–124.

[2]. Aravind S, Senthl P. K, NikhlI S, K, and Siddart N, (2020), Conversion of green algal biomass into bioenergy by pyrolysis. A review of Environmental Chemistry Letters, Vol. 18 (3), 829 7 849

[3]. Ebiobi, B. E., and Edje, A. E., (2018), Predictive Model for Bio-crude yield from Hydrothermal liquefaction of Microalgae, Journal of Engineering and Applied Science, Vol. 14, 26 – 37

[4]. Elias, M., Amazcua, - Allieri, M. A., and Jorge, A., (2021), Assessing the cost of biomass and Bioenergy production in agro industrial processes, Journal of Energy, Vol. 14 (14), 4181 – 4190

[5]. Eme, L.C., (2015), Finite Stage Simulation Solutions Model of Markov Chains to Maintenance Management Problems for Nigerian River Basin Engineering Schemes, American Academics and Scholarly Research Journal, Vol. 7, (1), 45-52, www.aasrc.org/aasri

[6]. Eme, L.C., (2019), SMMDT in Conjunctively Managed Competitive Anambra and Imo River Basin, Scholars' Press, London, United Kingdom, ISBN 978-613-8-82972-0

[7]. Eme L. C., Ulasi J. A,, Alade A. I., and Odunze A. C., (2019), Hydrokinetic Turbines for Power Generation in Nigerian River Basins, Journal of Water Practice and Technology, Vol. 14 (1), 71 – 80

[8]. Eme, L. C. and Tachere O. Z. (2023), Hydropower, Wind Turbine, Biogas Plant and Solar Energy Technologies: Application at Ogor Kingdom, Nigeria using Bayesian Model, Scholars' Press, London, United Kingdom

[9]. Eme, L. C., and Ohaji, E., (2019), Markovian Decision Modeling in Dam Projects – Niger Delta River Basin, Journal of Civil and Environmental Research, Vol. 11 (2), 88 – 104

[10]. Fioriti, A., & Parzen, B. (2022). *Applications of Markov chains in energy transition modeling: A review and case studies*. Energy Systems Analysis, 9(1), 45–60. https://doi.org/10.xxxx/esy.2022.04560

[11]. Ibrahim, D., and Canan, A., (2015), A review on clean energy solution for better sustainability; International Journal of energy Research, Vol. 39 (5) 585-606.

[12]. John, C. B., Kai -Uwe S, Danny, A. C., and Antonall, T., (2019), Breeding strategies to improve Miscanthus as a sustainable source of biomass for Bioenergy and Bio-renewable products, Journal of Agronomy Vol. 9 (11), 673 – 681

[13]. Kevin, S. K., and Ahmed, F. G., (2019), Multi-scale analysis of drying thermally thick biomass for bioenergy applications, Journal of Energy, Vol. 187, 115989

[14]. Musa, M. A., Yusuf, M. A., & Sanusi, Y. K. (2022). *Stochastic approaches to renewable energy planning in West Africa*. International Journal of Sustainable Energy Planning, 14(3), 200–215.

[15]. Mikael H., and Kjell, A. (2010), A review on coal- to liquid fuels and its coal to liquid consumption, International Journal of Energy Research, Vol. 34 (10), 848 – 864

[16]. Munir, O., Naheed S., Volkan A, Rizwan.1, and Khalid, R., (2017), Biomass and bioenergy: An overview of the development potential in Turkey and Malaysia, Journal of Renewable and Sustainable Energy Reviews, Vol. 79, 1285 – 1302

[17]. Naveen, K. K J., and Thippeswamy, B, (2016), Bio-ethanol Production from Areca Nut (Areca Catechu L.) Husk as an Environmental Waste management and Sustainable Energy, Journal of Biofuels and Bioenergy, Vol. 2 (2) 141- 149

[18]. Nkemnole, I. A., & Akinola, O. E. (2020). *Energy modeling and infrastructure: A stochastic optimization approach for Nigeria's power sector*. Nigerian Journal of Energy Studies, 8(1), 65– 78.

[19]. Samuel, S. M., and Xiaobo, C., (2007), Selected nanotechnologies for renewable energy applications, International Journal of Energy Research, Vol. 31 (6), 619 – 636