

Timur Nurgaliev

**Economic viability and risk of  
agricultural biogas production  
in Russia**

# **Economic viability and risk of agricultural biogas production in Russia**

Dissertation to obtain the doctoral degree of Agricultural Sciences  
(Dr.sc.agr.)

Faculty of Agricultural Sciences  
University of Hohenheim

Institute of Agricultural Engineering  
Tropics and Subtropics Group  
Prof. Dr. Joachim Müller

Institute of Economics and Management in Agribusiness  
Russian State Agrarian University – Moscow Timiryazev Agricultural Academy

Department of Management  
Prof. Dr. Valery Koshelev

submitted by  
Timur Nurgaliev

from Moscow, Russia  
2023

This thesis was accepted as a doctoral dissertation in fulfillment of the requirements for the degree “Doktor der Agrarwissenschaften” (Dr.sc.agr. / Ph.D. in Agricultural Sciences) by the Faculty of Agricultural Sciences of the University of Hohenheim on 24.05.2023

Date of oral examination: 03.11.2023

#### Examination Committee

Supervisor and Reviewer	Prof. Dr. Joachim Müller
Supervisor and Reviewer	Prof. Dr. Valery Koshelev
Additional examiner	Prof. Dr. Enno Bahrs
Head of the Committee	Prof. Dr. Stefan Böttinger

Schriftenreihe des Lehrstuhls für Agrartechnik in den Tropen und  
Subtropen der Universität Hohenheim  
herausgegeben von Prof. Dr. Joachim Müller

Band 2024/32

**Timur Nurgaliev**

**Economic viability and risk of agricultural  
biogas production in Russia**

D 100 (Diss. Universität Hohenheim)

Shaker Verlag  
Düren 2024

**Bibliographic information published by the Deutsche Nationalbibliothek**

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: Hohenheim, Univ., Diss., 2023

Copyright Shaker Verlag 2024

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-9452-7

ISSN 1867-4631

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren

Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9

Internet: [www.shaker.de](http://www.shaker.de) • e-mail: [info@shaker.de](mailto:info@shaker.de)

## **Acknowledgments**

I would like to express my gratitude to those who contributed to my Ph.D. works in many ways.

I would like to send my great gratitude to my supervisors, Prof. Dr. Joachim Müller from University of Hohenheim and Prof. Dr. Valery Koshelev from Russian State Agrarian University – Moscow Timiryazev Agricultural Academy for their double scientific guidance, support, motivation and encouragement.

My special thanks to Prof. Dr. Joachim Müller for his organizational support in University of Hohenheim, consultations, for his course “Renewable energy for rural areas” which helped me to improve my knowledge in renewable energies and for his expertise in biogas production technology which helped me to deal with challenges associated with description and modeling of anaerobic digestion technology.

My special gratitude to Prof. Dr. Valery Koshelev for his support, consultations, readiness to help and consult at any time, for his course “Project evaluation methods” which helped me to improve my qualification in evaluation of investment projects and for his expertise in mathematical modeling which helped me to deal with the challenges connected with application of linear programming methods.

My special gratitude to Mrs. Nugent, member of the Institute of Agricultural Engineering at University of Hohenheim, for her language editing, kind support, understanding and assistance. Mrs. Nugent’s help and words of support were invaluable many times – Mrs. Nugent is a hardworking and irreplaceable member of the Institute, who helps others, doing an enormous amount of work.

## Acknowledgments

---

I greatly acknowledge the scholarship awarded by the EU-Program Erasmus Mundus Partnerships (Action 2) via the project IAMONET-RU and the organizational support of the program coordinators at Universität Hohenheim, Dr. h.c. Jochem Gieraths, Dr. Angelika Thomas. Special thanks to the project coordinator Prof. Dr. Heinrich Schüle for his organizational support. This IAMONET-RU project made this work available to be carried out within the framework of the double scientific supervision by Prof. Dr. Joachim Müller from University of Hohenheim and Prof. Dr. Valery Koshelev from Russian State Agrarian University – Moscow Timiryazev Agricultural Academy.

Many thanks to my English teachers from University of Hohenheim Mrs. E. Mahood, Mrs. M. Canedy-Stelin, Mr. P. Jimenez and others, and my special thanks to my English teacher Mrs. Crystal Fisher from Anglo-German Institute (Stuttgart, Germany) who helped me to improve my English in 2013-2014.

I am very grateful to members of Russian State Agrarian University – Moscow Timiryazev Agricultural Academy Prof. Dr. Dmitriy Aleksanov. Prof. Dr. Aleksey Zinchenko, Prof. Dr. Valery Melnikov and others for their consultations. Special thanks to Dr. Vladimir Chinarov from Federal Research Center for Animal Husbandry named after Academy Member L.K. Ernst for his consultation in 2015.

I also want to thank the Doctors of medicine from Moscow who helped me to restore my health and thus to continue my work on this research, namely, Dr. med. Andrey Macey who helped me in 2015, Dr. med. Svetlana Duganova who helped me in 2022 and Dr. med. Dmitry Vasilyev who helped me in 2023.

And, finally, my thanks go to my parents Dr. Ildus Nurgaliev and Mrs. Galiya Nurgalieva for their limitless patience and support.

# Table of content

- Acknowledgments ..... i**
- Table of content ..... iii**
- List of figures ..... viii**
- List of tables ..... x**
- 1 General introduction ..... 1**
  - 1.1 Biogas production ..... 1
  - 1.2 Biogas potential estimation ..... 5
  - 1.3 Project modeling ..... 6
    - 1.3.1 Static and dynamic whole farm modeling ..... 6
    - 1.3.2 Linear programing and simulation modeling ..... 7
    - 1.3.3 Project evaluation methods ..... 7
  - 1.4 Project risk analysis ..... 9
    - 1.4.1 Sensitivity analysis ..... 9
    - 1.4.2 Monte Carlo simulation ..... 9
  - 1.5 Scenario analysis ..... 10
  - 1.6 Prospects and challenges ..... 10
  - 1.7 Objectives and structure of the research ..... 11
  - 1.8 References ..... 13
- 2 Part I: Biogas potential of agriculture ..... 18**
  - 2.1 Abstract ..... 18
  - 2.2 Introduction ..... 19
  - 2.3 Materials and methods ..... 23
    - 2.3.1 The Tambov region of the Russian Federation ..... 23
    - 2.3.2 Calculations ..... 27



2.4	Results and discussion .....	32
2.4.1	Electricity and heat production potential of the region.....	32
2.4.2	Potential of in-digestate N, P <sub>2</sub> O <sub>5</sub> and K <sub>2</sub> O production.....	36
2.4.3	Revenue potential of the region .....	37
2.5	Conclusion .....	42
2.6	Appendix A.....	44
2.7	References.....	49
<b>3</b>	<b>Part II: Simulation model for biogas project efficiency maximization ...</b>	<b>55</b>
3.1	Abstract.....	55
3.2	Abbreviations .....	56
3.3	Introduction.....	56
3.4	Materials and methods.....	64
3.4.1	Modeling framework .....	64
3.4.2	Efficiency evaluation procedure .....	68
3.4.2.1	Nomenclature .....	68
3.4.2.2	The object of study .....	68
3.4.2.3	Simulation model for substrate blend optimization (SBO).....	69
3.4.2.4	Linear programming for fertilizing plan optimization (FPO) .....	69
3.4.2.5	Simulation model for cost plan optimization (CPO).....	70
3.4.2.6	Linear programming model for farm production plan optimization (FPPO) 71	
3.4.3	Scenarios .....	71
3.4.4	Input data.....	71
3.4.5	Software .....	72
3.5	Results.....	73
3.5.1	Substrate blend .....	73
3.5.2	Fertilizing plan .....	75

3.5.3	Costs.....	75
3.5.4	Farm production plan.....	79
3.6	Discussion .....	83
3.7	Conclusion.....	85
3.8	Appendix A .....	87
3.8.1	Nomenclature .....	87
3.8.1.1	Elements .....	88
3.8.1.2	Subsets.....	92
3.8.1.3	Parameters .....	95
3.8.2	Simulation model for substrate blend optimization (SBO).....	96
3.8.2.1	Data input .....	96
3.8.2.2	Model output.....	98
3.8.3	Linear programming model for fertilizing plan optimization (FPO).....	99
3.8.3.1	Data input .....	99
3.8.3.2	Model output.....	103
3.8.4	Simulation model for cost plan optimization (CPO).....	105
3.8.4.1	Data input .....	105
3.8.4.1.1	Production costs of crop production .....	105
3.8.4.1.2	Costs of animal husbandry .....	112
3.8.4.1.3	Production costs of animal production .....	113
3.8.4.1.4	Post-production costs .....	114
3.8.4.2	Model output.....	117
3.8.5	Linear programming model for farm production plan optimization (FFPO).....	119
3.8.5.1	Data input .....	119
3.8.5.1.1	Lands .....	122
3.8.5.1.2	Crop production .....	123

3.8.5.1.3	Animal herd structure .....	123
3.8.5.1.4	Fodders, water and bedding straw for animals .....	124
3.8.5.1.5	Animal production .....	127
3.8.5.1.6	Anaerobic digestion .....	128
3.8.5.1.7	Dryer .....	133
3.8.5.1.8	Fertilizing .....	133
3.8.5.2	Model output .....	134
3.9	References .....	138
<b>4</b>	<b>Part III: Risk analysis of the biogas project .....</b>	<b>144</b>
4.1	Abstract .....	144
4.2	Abbreviations .....	145
4.3	Introduction .....	145
4.4	Materials and methods.....	149
4.4.1	Static model.....	149
4.4.2	Dynamic model .....	152
4.4.3	Risk analysis.....	158
4.4.3.1	Sensitivity analysis .....	160
4.4.3.2	Monte Carlo simulation .....	160
4.4.4	Input parameters .....	163
4.4.5	Scenarios .....	164
4.5	Results.....	166
4.5.1	Project efficiency maximization procedure.....	166
4.5.2	Risk analysis.....	169
4.5.2.1	Sensitivity analysis .....	169
4.5.2.2	Monte Carlo simulation .....	174

4.6	Discussion .....	177
4.7	Conclusion.....	179
4.8	Appendix A .....	184
4.9	References .....	190
<b>5</b>	<b>General discussion .....</b>	<b>196</b>
5.1	Biogas potential estimation.....	196
5.2	Biogas project modeling .....	196
5.3	Risk investigation of biogas projects .....	198
5.4	Software .....	200
5.5	Conclusions .....	201
5.6	Outlook.....	201
5.7	References .....	202
<b>6</b>	<b>Summary.....</b>	<b>206</b>
<b>7</b>	<b>Zusammenfassung .....</b>	<b>209</b>
<b>8</b>	<b>Publications.....</b>	<b>213</b>
8.1	Peer review papers.....	213
8.2	Conference papers .....	213
	<b>Author's declaration .....</b>	<b>215</b>
	<b>Curriculum vitae .....</b>	<b>216</b>

# List of figures

Figure 1-1. Annual world electricity generation by bioenergy technologies (IRENA, 2022a)..... 2

Figure 1-2. Annual world electricity generation by biogas in different parts of the world (IRENA, 2022b)..... 3

Figure 2-1. Distribution of electricity potential in the Tambov region of the Russian Federation for the period 2009 - 2018 ..... 34

Figure 2-2. Distribution of heat potential in the Tambov region of the Russian Federation for the period 2009 - 2018 ..... 35

Figure 2-3. Distribution of revenue potential in the Tambov region of the Russian Federation for the period 2009 - 2018 ..... 39

Figure 2-4. Distribution of municipal districts by their potential to produce energy and biofertilizer in 10<sup>9</sup> RUB..... 41

Figure 3-1. The scheme and data flows of efficiency evaluation procedure (EEP) 67

Figure 3-2. Crop rotation cycle ..... 68

Figure 3-3. Production costs of crops in fertilizing plans implying mineral fertilizers only and manure with mineral fertilizers in both scenarios in K RUB per ha ..... 77

Figure 3-4. Production costs of crops in fertilizing plans implying digestates as fertilizers in Scenario A and Scenario B in K RUB per ha ..... 78

Figure 4-1.Exemplary parameters of the biogas project with their typical trends according to their parameter subsets (the data series of each parameter is presented by the blue dots, the trends are presented by the black dashed lines) ..... 157

Figure 4-2. Elasticity coefficients of the biogas project parameters in % NPV ... 173

Figure 4-3. Probability distribution function of NPV in Scenarios 1a, 1b, 2a and 2b ..... 175

Figure 4-4.Inflation rate and key rate with their trends\* (Global finances, 2021; Infotables, 2021) ..... 187

## List of tables

Table 2-1. Average production of resources available for biogas production in the Tambov region of the Russian Federation during the period 2009 – 2018 (FSSS, 2020b).....	25
Table 2-2. Outputs of biogas production .....	28
Table 2-3. Substrates.....	28
Table 2-4. Resources for biogas production .....	29
Table 2-5. Municipal districts .....	29
Table 2-6. Biogas substrate characteristics .....	31
Table 2-7. Biogas potential of in the Tambov region of the Russian Federation for the period 2009 – 2018 in $M\ m^3$ .....	44
Table 2-8. Potential of in-digestate N production in the Tambov region of the Russian Federation for the period 2009 – 2018 in t.....	45
Table 2-9. Potential of in-digestate $P_2O_5$ production in the Tambov region of the Russian Federation for the period 2009 – 2018 in t.....	46
Table 2-10. Potential of in-digestate $K_2O$ production in the Tambov region of the Russian Federation for the period 2009 – 2018 in t.....	47
Table 2-11. Average revenue potential of substrates in the Tambov region of the Russian Federation during the period of 2009 – 2018 in $10^9$ RUB .....	48

Table 2-12. Ranks of substrates (10) and municipal districts (23) and their combination (230) in accordance to their revenue potentials (the more intense the colour, the higher the rank of this element) ..... 48

Table 3-1. Abbreviations ..... 56

Table 3-2. Substrate blend content in corresponding units per t of substrate blend 74

Table 3-3. Content of chemicals in different fractions of the digestate in kg per t of digestate ..... 74

Table 3-4. Main farm cash flows ..... 79

Table 3-5. Distribution of lands in ha ..... 81

Table 3-6. Farm production plan in corresponding units..... 82

Table 3-7. Elements used across all the models and their notations ..... 88

Table 3-8. Subsets  $R_i$  used across all the models and their notations..... 92

Table 3-9. Indexed subsets of fertilizer combinations and product applications used across all the models ..... 94

Table 3-10. Parameters used across all the models ..... 95

Table 3-11. Inputs of substrates per t of substrate blend  $a_{r,r'}$  in t per t ..... 97

Table 3-12. Volumes of AD inputs and outputs of substrates and additional ingredients  $a_{r,r'}$  and  $a_{j,r}$ ..... 97



Table 3-13. Content of DM in different fractions of the digestate $a_{jr}$ in t per t (FNR, 2010).....	98
Table 3-14. Substrate blend inputs and outputs $a_{r'r_{15}}$ and $a_{j'r_{15}}$ in corresponding units per t of substrate blend .....	98
Table 3-15. Contents of N, P <sub>2</sub> O <sub>5</sub> and K <sub>2</sub> O $a_{jr}$ in kg per t of different fractions of the digestate .....	99
Table 3-16. Assimilability of elements from fertilizers applied on the fields $a_{jq}$ in % .....	101
Table 3-17. Contents of elements in mineral fertilizers air and prices of mineral fertilizers $z_r$ .....	101
Table 3-18. Needs of crops for chemicals $a_{jr}$ , crop assimilability of elements from the soil $a'_{jr}$ and crop yields $a_{rq}$ .....	101
Table 3-19. Content of elements in the top soil $a_{jq}$ and their accessibility for crops from the soil $a'_{jq}$ .....	102
Table 3-20. Yield surplus coefficients of crops fertilized in accordance with different fertilizing plans $a_n$ .....	102
Table 3-21. Application rates of fertilizers $x_{r'q'n}$ in t per ha in Scenario A .....	103
Table 3-22. Application rates of fertilizers $x_{r'q'n}$ in t per ha in Scenario B .....	104
Table 3-23. Subsets of technological operations for crop production .....	106
Table 3-24. Application rates of fertilizers, seeds, water for spraying CPAs and CPAs $a_{r'q'r'n}$ for each fertilizing plan n in t per ha .....	108

Table 3-25. Prices of purchased resources $z_r$ .....	109
Table 3-26. Volumes of the resources spent on technical operations $a_{rwr'}$ and $a_{rwq}$ .....	110
Table 3-27. Subsets of resources needed for animal husbandry .....	112
Table 3-28. Volumes of the resources spent on animal husbandry $a_{rl}$ in corresponding units per animal.....	113
Table 3-29. Technological operations connected with producing animal products $r''' W_{6r}'''$ .....	113
Table 3-30. Volumes of the resources spent on technical operations connected with the production of animal products $a_{rwr'''}$ .....	114
Table 3-31. Subsets of technological operations connected with distribution of product and resources $W_{rs}$ and their contents .....	115
Table 3-32. Volumes of the resources spent on technical operations from subset $W_{rs}$ connected with using products in accordance with different uses $a_{rwr'}$ and subsets $R_w$ .....	116
Table 3-33. Production costs of crops $c_{qrn}$ in K RUB.....	117
Table 3-34. Animal husbandry costs $c_l$ in RUB per animal.....	118
Table 3-35. Production costs of animal products $c_{r''s}$ in RUB per t.....	118
Table 3-36. Distribution costs of crop and animal products $c'_{r''s}$ in RUB per t. ....	118
Table 3-37. Prices of commodity products $z_r$ in RUB per corresponding units .	121
Table 3-38. KR, IR and RAC in %.....	122

Table 3-39. Outputs $a_{r'r}$ .....	123
Table 3-40. Nutrient contents of fodders and minimal animals' needs for nutrition elements $a_{jr}$ in corresponding units .....	126
Table 3-41. Minimal contents of fodder $r$ fodder group $R_i$ in rations of animal group $l$ through fodder units $a'_{rl}$ .....	126
Table 3-42. Animals' needs for water and bedding $a_{rl}$ .....	127
Table 3-43. Outputs of animal products $a_{rl}$ in t per cow .....	128
Table 3-44. DM content in fodders $a_{j_2r}$ in % .....	128
Table 3-45. Demand of electricity $\beta$ in TJ .....	130
Table 3-46. Outputs of digestate fractions $a_{r'r_{21}}$ in t per t (Zorg Biogas AG, 2008) .....	131
Table 3-47. Prices of biogas equipment units $z_g$ , consumption capacities $a_{rg}$ and production capacities $a'_{rg}$ (Zorg Biogas AG, 2008) .....	132
Table 3-48. Project indicators .....	134
Table 3-49. Cash flows .....	134
Table 3-50. Lands $x_{qrn}^{opt}$ in ha .....	135
Table 3-51 - Volumes of products and resources in accordance with their uses $x_{rs}^{opt}$ in corresponding units .....	136
Table 3-52. Animal herd structure $x_l^{opt}$ .....	137
Table 3-53. Equipment units $x_g^{opt}$ .....	137

Table 3-54. Essential operating parameters and capacity utilization of AD equipment.....	137
Table 4-1. Abbreviations .....	145
Table 4-2. Input parameters in the dynamic model sorted by their subsets .....	163
Table 4-3. Values of the project indicators .....	167
Table 4-4. Production of the biogas and energy.....	167
Table 4-5. Substrate blend inputs and outputs in corresponding units per t of substrate blend .....	168
Table 4-6. Parameters of substrates.....	184
Table 4-7. Parameters having fluctuations and their values for the period 2009-2018 .....	185
Table 4-8. Measures of NPV variability in M RUB.....	188
Table 4-9. Biogas equipment sets.....	188
Table 4-10. Elasticity coefficients of the biogas project parameters in % NPV ..	189