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Methodology of GHG emissions assessment caused at the construction of energy facilities. Case study: Hydropower

I P Avilova, A E Naumov and M O Krutilova

Department of Assessment and Management of Real Estate, Belgorod State Technological University of V.G. Shukhov, Kostyukov St., 46, Belgorod, 308012, Russia

E-mail: kafeun@mail.ru

Abstract. As energy is the main 'fuel' for social and economic development, and since energy-related activities have significant environmental impacts, it is important to lower emissions and stabilize atmospheric CO_2 levels to avoid the worst predicted effects of climate change. Reducing energy consumption and costs is becoming central to planning, construction, and use of energy construction facilities from an environmental and economic point of view. Each energy source has advantages and disadvantages referred to: operating costs, environmental impact, and other factors. Each generation method produces some greenhouse gases (GHG) in varying quantities through construction, operation, and decommissioning. Some generation methods like coal fired plants release the majority of GHGs during operation. Others, such as wind power and hydro power release the majority of emissions during construction and decommissioning. Normalizing the lifecycle emissions with electrical generation allows a fair comparison of different generation methods on a per gigawatt-hour basis.

Keywords: GHG emissions, hydropower plant construction, eco-oriented assessment of the estimated cost, sustainability, green building.

1. Introduction

The changes in the energy industry over the past 20 years have been significant. The growth in energy consumption has been higher than anticipated even in the high-growth scenarios. The energy industry has been able to meet this growth globally assisted by continuous increases in reserves' assessments and improving energy production and consumption technologies. The results of the 2013 WEC World Energy Resources survey show that there are more energy resources in the world today than 20 years ago, or ever before [1].

Providing the benefits of electricity to hundreds of millions of people around the World is a key challenge of this century. In the International Energy Agency's World Energy Outlook 2010, global energy demand was expected to rise 1.4% per year on average to 2035, assuming no change in current business-as-usual energy policy [2]. In 2010, actual global energy use jumped by 5.6%, the largest single year increase since 1973. The current global energy mix remains heavily weighted towards conventional fossil fuels. Coal's share of global energy consumption was 29.6%, the highest since 1970. By 2030, it is expected that World energy consumption will rise from just under 12 btoe (billions of tonnes of oil equivalent) to over 16 btoe, with much of this growth occurring in non-OECD countries, particularly China and India [3]. As energy is the main 'fuel' for social and economic development, and since energy-related activities have significant environmental impacts, it is important

to lower emissions and stabilize atmospheric CO_2 levels to avoid the worst predicted effects of climate change. From an environmental and economic point of view, reducing energy consumption and costs is therefore becoming central to planning, construction, and use of energy construction facilities.

Energy facilities' emissions should be analyzed according to a life cycle analysis (LCA) approach, including emissions at the construction stage [4]. Life cycle GHG emissions for an energy generation facility include emissions associated with the construction and eventual decommissioning of the facility which called indirect emissions, as well as any emissions resulting from the facility's operation, which called direct emissions. Power plants consist of:

- Energy construction property (ECP),
- Energy construction equipment (ECE).

Power plant's emissions should be analyzed according to a life cycle analysis (LCA) approach, including emissions at the construction phase of the facility (indirect emissions).

Table 1. Categories of LCA emissions.

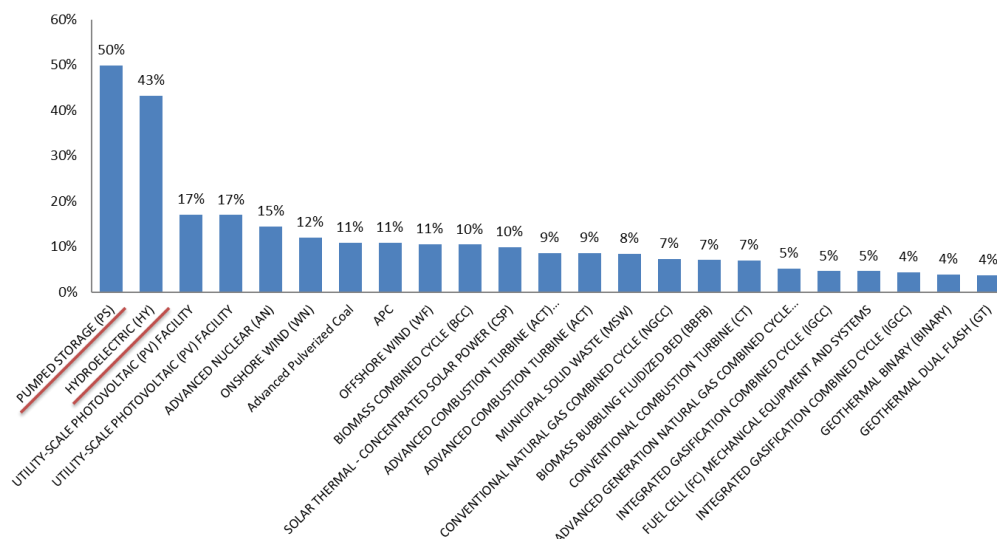| Energy construction property (ECP)	Energy construction equipment (ECE)
Indirect emissions	**Direct emissions**
Infrastructure	Combustion of fuels
Construction and installation work	Operational fuel use
Building Materials	Other emissions from operation (e.g., flooded land)
Transport	Goods and services consumed during operation
Decommissioning and waste disposal	

Figure 1. Rank of power plant types by Construction Material and Installation Cost (CMIC) in Total Project Cost (TPC).

Sources of indirect emissions for power plants include emissions from: development of infrastructure (e.g., roads and transmission lines), construction and installation work on the facility itself, manufacturing of building materials and equipment, transportation of materials and workers, decommissioning and waste disposal. According to Dones et al. [5], the major sources of GHG emissions for hydropower within these categories include cement and steel production, and the use of diesel and electricity. Raadal et al. [6] states that "the major contributing factors to the infrastructure GHG emissions are

concrete production and the transportation of rocks in the construction of dams and tunnels". In order to substantiate the relevance of the topic, we should to compare the civil structural material and installation cost (CSMIC) in relation to total project cost (TPC) for a range of different power plants types. It's important to note that there are many energy facilities that require high construction costs. Using the data U.S. Energy Information Administration [7] a ranking was conducted figure 1.

2. Materials and Methods

We propose using the following methodologies:

- Methodology for mathematical relation of the scope of main energy-consuming works and building materials, and the capacity of the hydropower plants;
- Methodology assessment of GHG emissions per unit for basic building materials applied to construction of hydropower plants (concrete, steel framework, coarse aggregates for backfilling, etc.);
- Methodology for determining of GHG emissions per unit for the main works carried out in-situ to construct the structures of hydropower stations (soil development, stone development, soil and cofferdam filling, pouring the concrete, resources delivering, etc.).

2.1. Methodology of determining the scope of main energy-consuming works and building materials, depending on the capacity of the hydropower plants.

Approximation method. For determining of possible correlation among volumes of basic construction materials and construction works consumed at modern HPS' construction and generating power of HPS in MW non-linear regression analysis was carried out. In Nonlinear regression analysis observational data are modeled by a function which is a nonlinear combination of the model parameters and depends on one analyzed variable. For approximation in techno-economical processes what are always consist of non-linear (irregular, stochastic) and linear (regular, systematic) parts, K-polynomials proposed by author are useful, relevant and confident [9].

K-polynomial of nth degree means the symmetrical mathematical expression of normal and inverse powered variables as follows:

$$Y = a_{(-n)}x^n + a_{(-(n-1))}x^{n-1} + \ldots + a_0x^0 + \ldots + a_{n-1}x^{-(n-1)} + a_nx^{-n}, \tag{1}$$

where a_i – constants, x – single variable, x^0 – dummy term (always equal to 1), used for structure's clearness.

Left part of K-polynomials (before dummy) used for approximation of non-linear parts in approximated processes, right one (after dummy) used for approximation of linear parts in approximated processes. Proposed K-polynomial could be easily converted to:

1. linear function (i = 1; $a_{(-1)}\ldots a_0$ = const, a_1 = 0);
2. polynomial of nth degree ($a_{(-n)}\ldots a_0$ = const; $a_1\ldots a_n$ = 0);
3. exponential of nth degree ($a_n\ldots a_0$ = const; $a_{(-n)}\ldots a_{(-1)}$ = 0);

or remain complex to unite advantages of all above types. These confirms utility of the proposed expression in techno-economical analysis to handle multifactorial processes.

Correlation among volumes of basic construction materials/works and generating power of HPS offered to be expressed as K-polynomial of 1st degree as follows:

$$Y = ax + bx^{-1}, \tag{2}$$

where a, b are constant, x – analyzed variable.

All variables analyzed separately (number of freedom degrees is 1, variables row consist of 8 numbers), according initial suggestion for significant correlation of designed power of HPS and following:

a) basic construction works:

- Earth Excavation,
- Rock Excavation,
- Earthfill Dam,
- Cofferdam construction,
- RCC Dam construction.

b) basic construction materials:

- Structural steel,
- Concrete.

The data are fitted by a least squares method — standard approach in regression analysis to the approximate solution. Significance of models checked by R^2 adjusted determination. Models characterized by $R^2_{adj} > 0.75$ are significant. Utility of models was verified by Fisher's testing at fixed confidence level 0.95. Models characterized by F-test $<$ F $(0.05;1;6)$ are utility and could be taken into account for further analysis.

2.2. Methodology assessment of GHG emissions per unit for basic building materials applied to construction of hydropower plants (concrete, steel framework, coarse aggregates for backfilling, etc.).

The second methodology considers GHG emissions per unit for basic building materials such as concrete and steel. Using the emission data, we can determine the certain amount of emissions per unit volume. To do this better use a special calculator, allowing to get the current value of GHG emissions by entering the value of building material and selecting parameters [10].

2.3. Methodology for determining of GHG emissions per unit for the main works carried out in-situ to construct the structures of hydropower.

The third methodology considers determining GHG emissions per unit for the main works carried out in-situ to construct the hydropower station. Using the data of U.S. Environmental Protection Agency [11] GHG emissions for excavators per 1 m^3 were determined as following in table 1.

3. Results

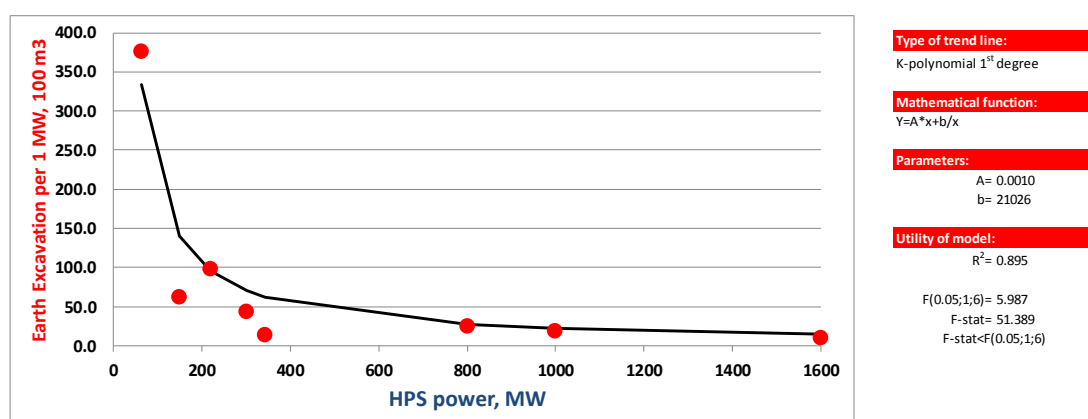*3.1. Approximations for Russian power plants.*

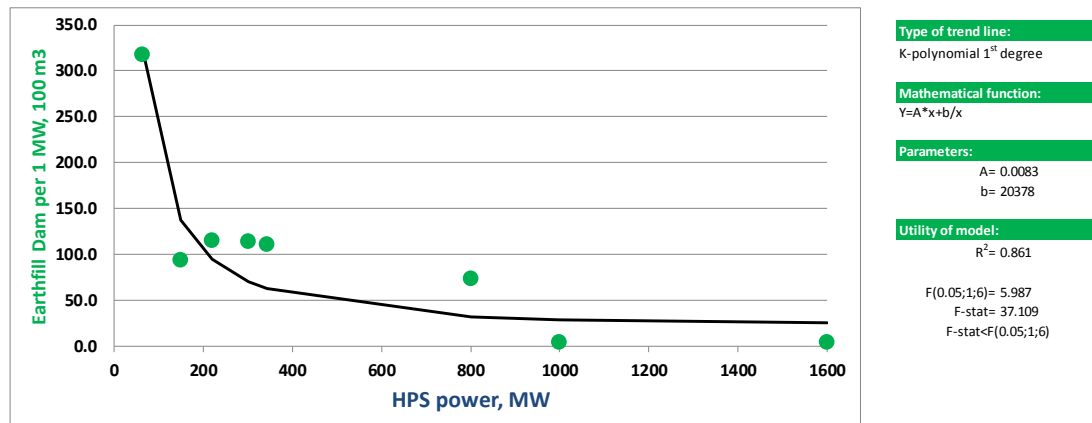**Figure 2.** Non-linear regression for Earth Excavation per 1 MW.

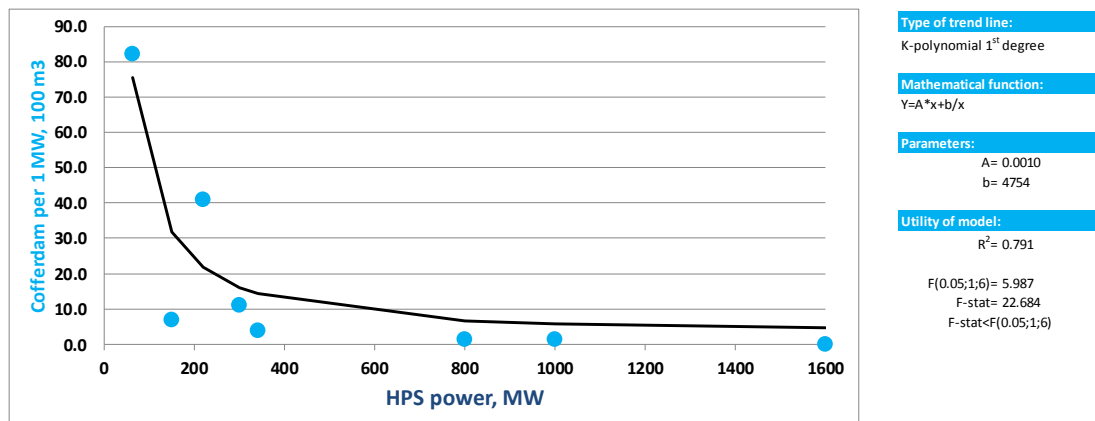**Figure 3.** Non-linear regression for Earthfill Dam per 1 MW.
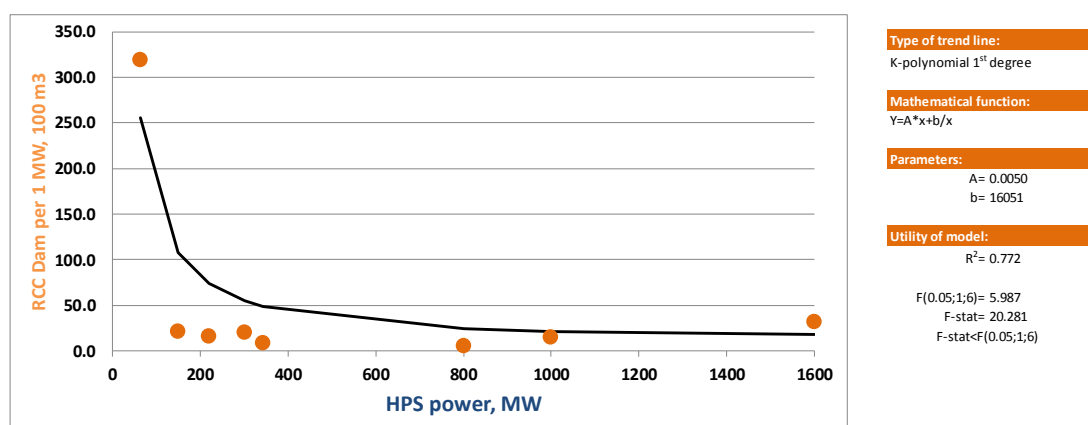

Figure 4. Non-linear regression for Cofferdam per 1 MW.
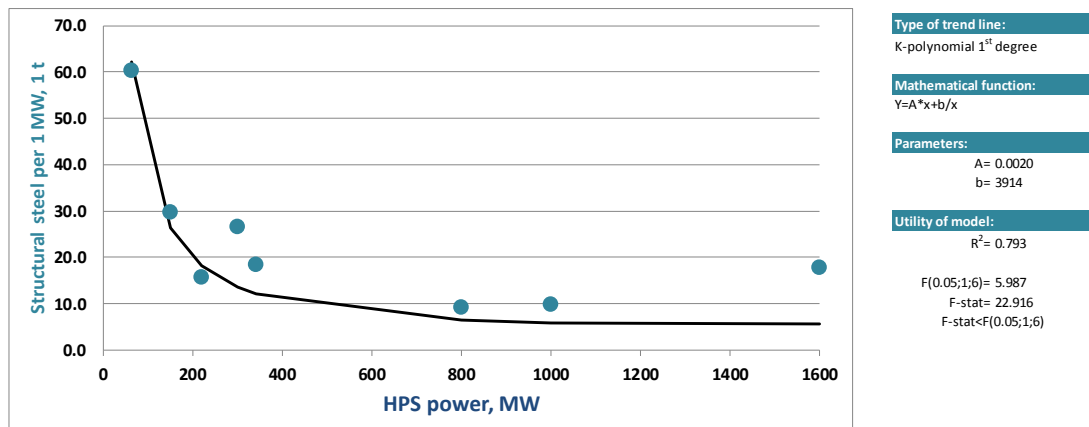

Figure 5. Non-linear regression for RCC Dam per 1 MW.

Figure 6. Non-linear regression for Structural steel per 1 MW.

3.2. Approximations for Russian and foreign power plants.

Table 2. Earth excavation consumed at modern HPS' construction, general [13].

HPS power, MW	63	150	220	300	342	400	476	600	707	800	824	1000	1600	1224	1800
Earth Excavation m³	1000	2370	922	2148	1309	480	200	200	688	2500	2022	1000	1850	1550	4000	4000

* blue marked — foreign plants (USA, Canada), not marked – Russian plants.

Table 3. Earth excavation consumed at modern HPS' construction, per 1 MW.

HPS power, MW	150	220	300	342	400	476	600	707	800	824	1000	1600	1224	1800
Earth Excavation per 1 MW, 100 m³	61.5	97.6	43.6	14.0	5.0	4.2	11.5	35.4	25.3	12.1	18.5	9.7	32.7	22.2

* blue marked — foreign plants (USA, Canada), not marked – Russian plants.
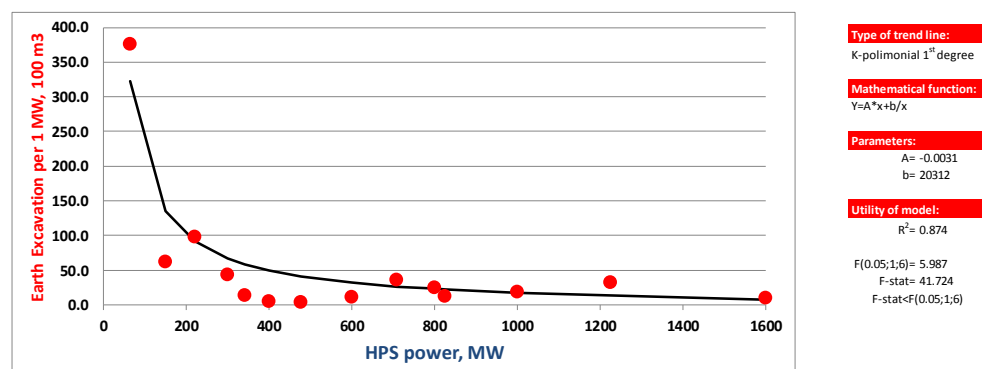

Figure 7. Non-linear regression for Earth Excavation per 1 MW.

Table 4. Cofferdam construction consumed at modern HPS' construction, general [14].
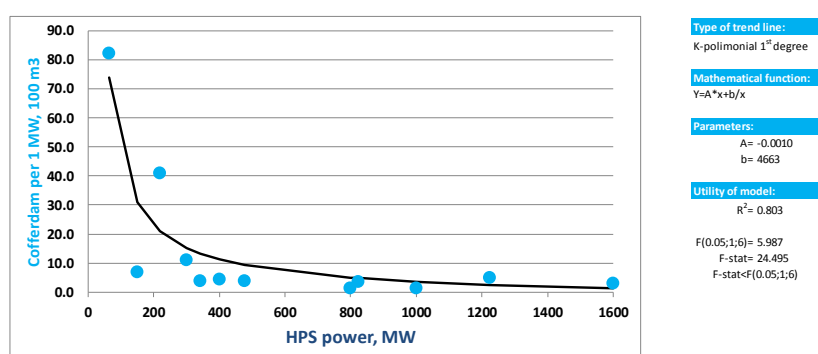
HPS power, MW	63	150	220	300	342	400	476	800	824	1000	1224	1600
Cofferdam, 1000 m³	517	105	901	335	129	180	180	107	300	133	600	500

* blue marked — foreign plants (USA, Canada), white marked – Russian plants

Table 5. Cofferdam construction consumed at modern HPS' construction, per 1 MW.

HPS power, MW	63	150	220	300	342	400	476	800	824	1000	1224	1600
Cofferdam per 1 MW, 100 m³	82.1	7.0	41.0	11.2	3.8	4.5	3.8	1.3	3.6	1.3	4.9	3.1

* blue marked — foreign plants (USA, Canada), white marked – Russian plants

Type of trend line:
K-polimonial 1st degree

Mathematical function:
Y=A*x+b/x

Parameters:
A= -0.0010
b= 4663

Utility of model:
R^2= 0.803

F(0.05;1;6)= 5.987
F-stat= 24.495
F-stat<F(0.05;1;6)

Figure 8. Non-linear regression for Cofferdam per 1 MW.

Table 6. RCC Dam construction consumed at modern HPS' construction, general [15].

HPS power, MW	63	65	150	220	300	342	600	707	800	824	1000	1224	1600	2028
RCC Dam, 1000 m³	2010	1790	320	354	602	283	4893	700	447	300	1491	700	5119	700

* blue marked — foreign plants (USA, Canada), white marked – Russian plants

Table 7. RCC Dam construction consumed at modern HPS' construction, per 1 MW.

HPS power, MW	63	65	150	220	300	342	600	707	800	824	1000	1224	1600	2028
RCC Dam per 1 MW, 100 m³	319	276	21.3	16.1	20.1	8.3	81.6	9.9	5.6	3.6	14.9	5.7	32.0	3.5

* blue marked — foreign plants (USA, Canada), white marked – Russian plants

Type of trend line:
K-polimonial 1st degree

Mathematical function:
Y=A*x+b/x

Parameters:
A= -0.0034
b= 16893

Utility of model:
R^2= 0.844

F(0.05;1;6)= 5.987
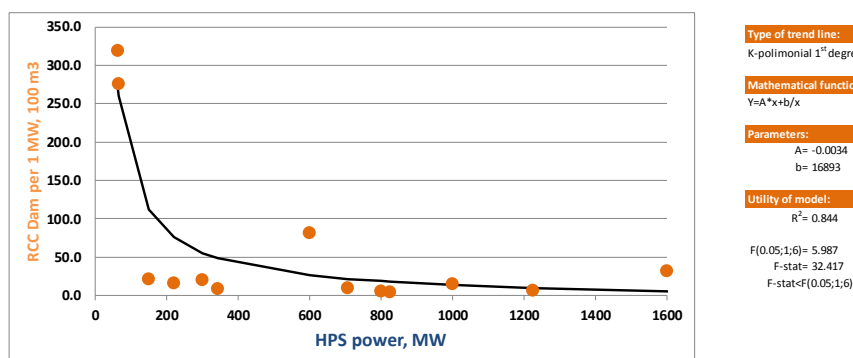F-stat= 32.417
F-stat<F(0.05;1;6)

Figure 9. Non-linear regression for RCC Dam per 1 MW.

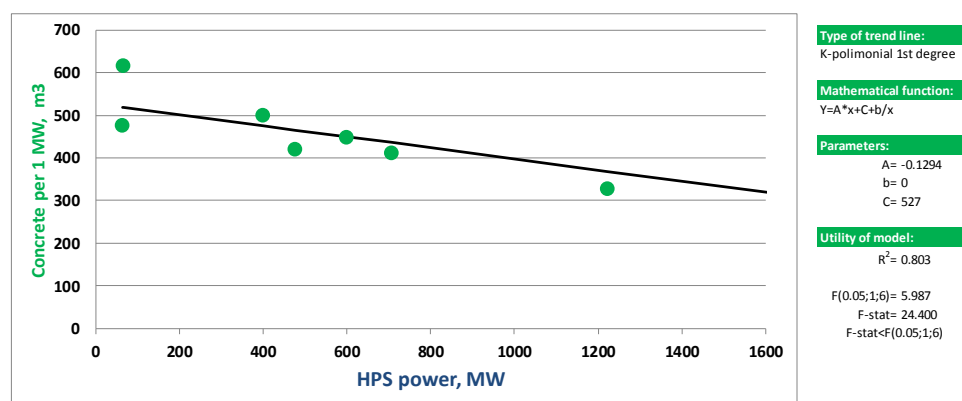**Table 8.** Concrete consumed at modern HPS' construction, general [16].

HPS power, MW	63	65	400	476	600	707	1224	1800	2028
Concrete, 1000 m3	30	40	200	200	268	290	400	550	600

* blue marked — foreign plants (USA, Canada), white marked – Russian plants

Table 9. Concrete consumed at modern HPS' construction, per 1 MW.

HPS power, MW	63	65	400	476	600	707	1224	1800	2028
Concrete per 1 MW, m3	476	615	500	420	447	410	327	306	296

* blue marked — foreign plants (USA, Canada), white marked – Russian plants

Figure 10. Close to linear regression for RCC Dam per 1 MW.

Volumes of basic construction materials and construction works consumed at modern HPS' construction have significant correlation with volume of generating power of designated HPS in MW. Correlations are approximated by proposed K-polynomial of 1st degree, suitable for further analysis and management [17]. Volumes of basic construction materials and construction works per 1 MW of generated power inversely depend on total designated power of HPS, decrease by power increasing drastically till designated power 400 MW and slightly after 400 MW till 1000-1500. Each obtained MW of HPS energy after 600-800 MW of designated power costs equally, so the more power HPS designed for the more profitable and less environmentally harmful energy is.

3.3. Methodology assessment of GHG emissions per unit for basic building materials applied to construction of hydropower plants (concrete, steel framework, coarse aggregates for backfilling, etc.)

Table 10. GHG Emission calculator: Basic materials [18, 19].

Initial data		GHG Calculation	
Steel volume, t	150		
Production process	ISM	Estimated GHG emission per t, t	2,0
		Total GHG emission for the whole scope of material, t	**300**
Concrete volume, cub.m	58000	Estimated GHG emission per 1 cub.m, kg	1,51
		Total GHG emission for the whole scope of material, t	**87,6**
		Total GHG emission, t	**387,6**

3.4. Methodology for determining of GHG emissions per unit for the main works carried out in-situ to construct the structures of hydropower.

Table 11. Power-productivity of excavators [20].

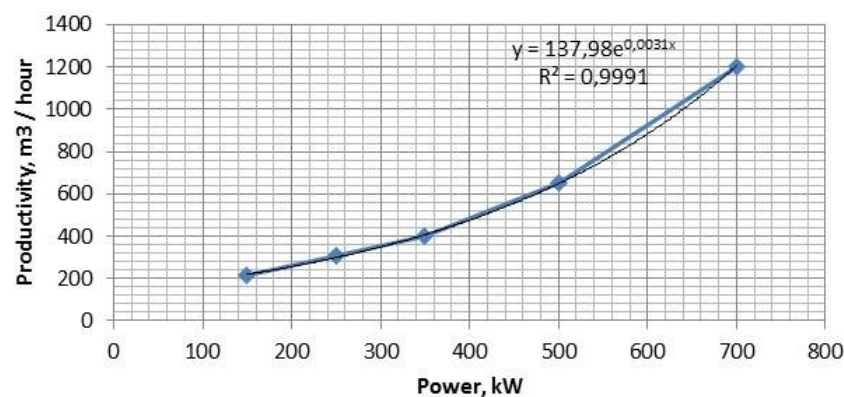| Excavator	Type 1	Type 2	Type 3	Type 4	Type 5
Power, kW	150	250	350	500	700
Bucket capacity, m^3	1,5	3	5	10	20
Full cycle time, s	25	35	45	55	60
Productivity, m^3 / hour	216	309	400	655	1200

Figure 11. Power-productivity of excavators.

Table 12. GHG Emission for excavators [21].

Excavator	Komatsu GD655	Cat D4CXL	Cat D4CXL	Comatsu C340C	John Deere 310G
Productivity, cub.m/hr	360	432	409	525	514
Power. kW	128	232	255	330	349
GHG Emission, g/kW-hr	10,372	11,84	8,715	16,145	11,83
GHG Emission, g/hr	1327,62	2746,88	2222,33	5327,85	4128,67
GHG Emission per 1 m^3, g	3,688	6,359	5,434	10,148	8,032

4. Conclusion

Thereby using all three engineering techniques, we can independent and simultaneously get an estimation of GHG emissions at the construction stage of HY power plant of different capacities, constructed with different building equipment and distances for material's delivery. As a main result of the research we have GHG Emission calculator for different kinds of main construction works and materials. Using the technique engineer in general can calculate the total GHG emissions caused by construction of different types, using a design and estimate documentation of a power plant and GHG Emission calculator.

For large hydropower projects, the capital costs are dominated by the civil works. The cost of civil works is influenced by numerous factors pertaining to the site, the scale of development and the technological solution that is most economic [22]. Nearly 500 hydropower projects totaling more than 50,000 MW have been served by Black & Veatch worldwide [23]. The Black & Veatch historical database incorporates a good understanding of hydroelectric costs. Black & Veatch used this historical background to develop the cost estimates vetted in the WREZ stakeholder process and to subsequently update that pricing and adjust owner's costs as necessary [24].

Table 13. GHG Emission calculator: Hydropower plant construction.

INITIAL DATA			
Plant's parameters		**Volume**	
Designated power, MW		250	
Materials' transportation average distance, km		25	
Construction works	**Volume**	**Machines type**	**Machines' model**
Excavated Earth, cub.m	2380000	H.Excavator	Case CX210B
Earfilled Dam, cub.m	3220000	Bulldozer	Hitachi FD255
Cofferdam, cub.m	750000	H.Grab	Terex MHL364
Construction Materials	**Volume**	**Producer**	**Technology**
RC, cub.m	250000	EuroCon	Dry
Structural Steel, t	3 650	Mittal	ISM
GHG CALCULATION			
Machines		**Materials**	
Excavators	**Volume**	**RC**	**Volume**
Excavator's engine power, kW	110	Estimated GHG for cement production, g/t	15,00
Excavator's bucket, cub.m	0,75	Estimated GHG emission for coarse aggregate, g/cub.m	8,50
Estimated productivity, cub.m/hr	205	Estimated GHG emission for fine aggregate, g/cub.m	2,50
Estimated GHG emission, g/cub.m	5,30	Estimated GHG emission for mix production, g/cub.m	0,80
Estimated GHG emission total, t	12,61	Estimated GHG emission for mix transportation, g/cub.m/km	3,50
		Estimated GHG emission total, t	25,39
Bulldozers		**Construction Steel**	
Bulldozer's engine power, kW	175	Estimated GHG emission for steel production, g/t	2 500
Buldozer's blade, cub.m	2,50	Estimated GHG emission for steel transportation, g/t/km	2,50
Estimated productivity, cub.m/hr	150	Estimated GHG emission total, t	9,35
Estimated GHG emission per 1cub.m	4,15	**Total GHG emissions caused by materials, t**	**34,74**
Estimated GHG emission total, t	13,36		
Grabs			
Grab's engine power, kW	190		
Grab's bucket, cub.m	2,00		
Estimated productivity, cub.m/hr	130		
Estimated GHG emission per 1cub.m	8,40		
Estimated GHG emission total, t	6,30	**Total GHG emissions caused by construction, t**	**67,02**
Total GHG emissions caused by machines, t	**32,28**	**Total GHG emissions caused by construction, t/MW**	**0,268**

Similar to geothermal technologies, the cost of hydropower technologies can be site-specific. Numerous options are available for hydroelectric generation; repower in an existing dam or generator, or installing a new dam or generator, are options. As such, the cost estimates shown in this report are single-value estimates and may not be representative of any individual site. 2010 capital cost for a 500 MW hydropower facility was estimated at 3,500 $/kW +35%. Table 22 presents cost and performance data for hydroelectric power technology [25]. For the most types of ECP necessary volumes of basic construction materials and machine-hours could be estimated approximately using some confident margins under given level of confidence.

Table 14. Eco-penalties

Group of eco-penalties	Reasons for eco-penalties	Eco-penalties (additional cost), $ for ECP type				
		wind	NG	Solar PV	Hydro	Fossil-L
Construction material (for 1 measurement unit of consumed material)	Concrete, m3	12	20	16	12	12
	Steel for rebars, t	114	139	145	118	192
	Steel for framework, t	156	156	140	165	112
	Ceramics, etc, t	32	34	40	23	27
Transportation (for 1000 t/km of average distance to construction plants)	up to 20 km	9	8	7	9	10
	21-49 km	9	9	6	6	8
	more than 50 km	7	8	8	6	5
Installation (for 100 machine-hours of machine/vehicle in installation processes)	up to 20 machines/vehicles	6	6	6	8	7
	21-49 machines/vehicles	5	6	6	7	6
	more than 50 machines/vehicles	5	4	5	4	4
In-situ energy consumptions for facilities and workers accommodation (for 10 worker-day at construction site)	up to 50 workers	15	15	10	12	11
	51-199 workers	8	9	11	11	11
	more than 200 workers	9	6	8	7	9
In-situ energy consumptions for tools and engines (for 1 day of 10 tool/engine at construction site)	up to 20 tools/engines	20	20	21	21	26
	21-49 tools/engines	18	16	16	16	17
	more than 50 tools/engines	13	14	12	12	13

For example, constructing of typical hydro power station ECP requires for each MW of energy 30-50 m3 of ready-mix concrete. Each exact number in the margins is acceptable according to construction details: region, season of year, engineering and transportation level of neighborhood's development, etc. The same reasons makes transportation distances, in-situ energy consumers' number and other significant details of calculation equally uncertain. Due to this, best mathematical procedure to handle uncertain source data and calculate confident figures of energy consumption per 1 unit of ECP is Monte-Carlo's imitation modelling and statistical operation with generated variables in data-panels [26].

All kinds of penalties for usability purposes are to be separated into 4 main groups: 1) construction materials; 2) transportation; 3) installation; 4) in-situ energy consumptions.

To avoid negative influence of money power deprivation and discounting all the penalties could be expressed in basic money equivalent fixed for 2018 year. All further estimation could be easily converted to current prices according to single deflator-index, estimated annually by means of dynamic construction market analysis (subject of additional researches). After calculating all penalties per 1 measurement unit for each used material, construction item and machine-hour one can recalculate average construction cost of energy (ACCE), taking caused (embodied) environmental harm into account. According to this calculations ACCE could be ranked like this:
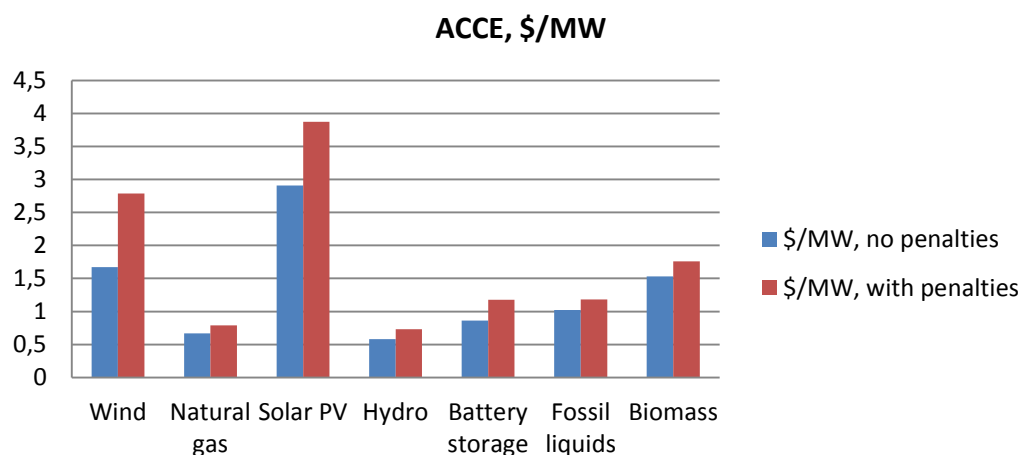

Figure 12. Average construction cost of energy

Table 15. Rank of energy station types by ACCE

Before penalties		After penalties	
Power plant type	**ACCE, $/MW**	**Power plant type**	**ACCE, $/MW**
1. Hydro	0.58	1. Battery storage	0.92 ↑58%
2. Natural gas	0.67	2. Hydro	1.12 ↑67%
3. Battery storage	0.86	3. Fossil liquids	1.19 ↑38%
4. Fossil liquids	1.02	4. Natural gas	1.30 ↑27%
5. Biomass	1.53	5. Biomass	1.90 ↑24%
6. Wind	1.67	6. Wind	2.79 ↑67%
7. Solar PV	2.91	7. Solar PV	3.46 ↑19%

Thus, some types of ACCE will increase its self-cost, other – decrease, and one can more confident and relevant estimate the ACCE or desirable or planned energy type according to embodied environmental harm caused by ECP construction process.

Acknowledgments

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