Deployment of bio-CCS: case study on Waste-to-Energy

Fortum Oslo Varme (FOV), Oslo, Norway

Contribution of IEA Bioenergy Task 36 to the inter-task project *Deployment of bio-CCUS value chains*

May 2021

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Preface

Substantial amounts of negative emissions may be required if global climate change is to be limited to well-below 2°C above pre-industrial levels, as is the ambition of the 2015 Paris Climate Agreement. Among the different negative emissions options available, bioenergy with carbon capture and storage, also referred to as bio-CCS or BECCS, is arguably one of the most commonly discussed in climate policy debates.

Up until recently, bio-CCS was primarily discussed in terms of its potential and drawbacks over very long timeframes, e.g., 2050 and beyond, but there is now growing focus on more near-term aspects. The IEA Bioenergy inter-task project *Deployment of BECCS/U value chains* runs 2019-2021 and strives to provide insights about the opportunities and challenges pertaining to taking BECCS from pilots to full-scale projects. To this end, the project puts focus not only on technological aspects but also on how BECCS business models could be set up and the role that public policy could play in enabling sustainable deployment of BECCS. Focus in the project is on the CO_2 capture, transportation and storage phases of the supply chain. Upstream biomass feedstock supply systems are only touched upon very briefly, as these issues are analyzed to great detail in other IEA Bioenergy work.

An important characteristic of BECCS is that it can be implemented in a broad range of sectors - basically any setting where there are biogenic emissions of CO_2 available in sizeable quantities. This includes generation of heat and power in various contexts, but also industrial facilities like cement production, pulp & paper mills or ethanol plants. The specifics related to BECCS implementation can however vary quite substantially from sector to sector. This is partly because of differences in technological factors like CO_2 concentrations, but also a result of how different sectors operate under widely varying commercial and regulatory conditions.

This case study is part of a series of studies carried out under the *Deployment of BECCS/U Value Chains* project with the aim to highlight these sector-specific characteristics. The case studies provide deeper insights into the key aspects that come into play for companies that are in the process of setting up value chains for capture, transportation and sequestration or utilization of biogenic CO_2.

Summary

Despite growing global ambitions towards increased material recycling, waste-to-energy (WtE) will likely continue to play an important role in coming decades as a means of managing waste streams that for one reason or another may be difficult to treat otherwise. Typically, 40-60% of municipal solid waste (MSW) used as input in WtE facilities are of biogenic origin in developed countries, meaning that implementation of carbon capture and storage (CCS) to WtE partially can be classified as bio-CCS and lead to negative CO_2 emissions. There are currently several ongoing projects exploring CCS in WtE settings, and this case study presents what is arguably the project that has come the farthest: the FOV (Fortum Oslo Varme) WtE plant in Oslo, Norway.

There is currently plenty of CCS activities in Norway, both in the form of the development of a transport & offshore storage infrastructure project called Northern Lights, and in the form of point source capture projects. The FOV project has been initiated as part of a broader ambition of the city of Oslo to reduce its GHG emissions by 95% in the period 2009-2030. With the FOV plant being the city's largest single emission source, it is imperative to address these.

A first pilot phase of the Fortum project started in 2015 and since then, a series of pilot campaigns and feasibility studies have been conducted on an amine-based CO_2 capture system. In parallel, the Norwegian government has investigated and evaluated different options for facilities deemed suitable to be included in the demonstration of a full-scale CCS supply chain. In Autumn 2020, it was announced (under the name Longship) that the FOV project would be one of two facilities that would get governmental funding (the other one being the Heidelberg Norcem cement plant) together with Northern Lights for permanent storage. However, while the Norcem plant (and Northern Lights) would be (presumably 80-90%) funded by the government, funding for the FOV WtE plant has been conditioned on it being able to provide 50% co-funding (~300 million €) from own funding and other sources, the EU Innovation Fund offering the best opportunity. At the time of writing (April 2021), it is uncertain if this additional funding will be secured. This is now the key factor determining the time plan for full-scale deployment of the CCS project at Fortum, which according to the original time plan is due to come online in 2024. The EU Innovation Fund will decide in Q4 2021 if FOV receives support. With a positive decision, the CCS plant could be operational by 2026-2027. Despite these remaining uncertainties pertaining to funding, the recent years have seen several other actors in Norway initiating WtE CCS projects.

Acknowledgments

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1 Introduction

1.1 WASTE TO ENERGY (WTE) AND CCS (CARBON CAPTURE AND STORAGE)

Globally, over 2 billion tons of municipal solid waste (MSW) is generated every year. A large share of these volumes is currently not treated by means that are satisfactory from an environmental, resource and health perspective (Kaza et al. 2018). These volumes are increasing as the global population grows larger and increasingly affluent. Even in the light of increased ambitions for material re-use and recycling, there will likely continue to be demand for incineration with energy recovery and advanced flue gas cleaning. There are still many waste streams that for various reasons may be more difficult to treat by other means and that otherwise could have ended up in landfills which in places still are uncontrolled, open dumps. In addition to its value as a waste management pathway, incineration can also be used as a mean of generating electricity and/or heat, the latter for use in district heating systems or by industry.

Although proportions vary over time and with location, MSW incinerated in waste-to-energy (WtE) facilities usually consists of 40-60% biogenic materials in the form of e.g., paper, food, wood, cardboard or leather, with the remaining being material of fossil origins in the form of plastics and synthetics. Consequently, application of carbon capture and storage (CCS) to WtE systems can at least partially be classified as bio-CCS and has the potential to enable negative CO_2 emissions. At the time of writing, WtE CCS projects are in various phases of planning or piloting in for example Japan, the Netherlands and Sweden (Kearns 2019; Vattenfall 2020). The one project that has arguably come the closest to commercial deployment however is the one that we will focus on in this case study, the facility operated by Fortum Oslo Varme (FOV) in Oslo, Norway.

1.2 THE FORTUM OSLO VARME (FOV) CCS PROJECT IN OSLO - BACKGROUND

CCS has a long history in Norway, as CO_2 from off-shore natural gas production has been captured and sequestered in off-shore deposits since 1996. In addition to the operation of these facilities, the country has dedicated a substantial amount of resources to R&D activities on capture, transportation and storage of CO_2. In 2019, the Norwegian government announced its ambition to set up, demonstrate and commercialize a full-scale CCS supply chain based on an open-access infrastructure. This will allow for CO_2 from point sources all over Europe to be transported via ship to an injection point on the Norwegian coast, from which it is transported in a subsea pipeline to an offshore permanent storage site.

In addition to the development of the transport and storage infrastructure, there has also been substantial activities in Norway focusing on the *capture* component of the CCS supply chain, with several different sectors and facilities being considered as possible demonstration projects. This case study is focused on one of these, FOV WtE facility in Oslo.

The City of Oslo decided in the early 2010s to adopt a strong sustainability vision and set itself ambitious Green Goals, among others a 95% reduction in CO_2 emissions within 2030 compared to 2009 (Oslo Kommune 2019). The strategy includes CO_2 reduction measures such as a car-free city centre and the phasing out of fossil-based heating. In addition to this, is the project to implement CCS at the FOV WtE plant - the largest CO_2 single point emitter in Oslo with approximately 400 000 tons CO_2 emissions per year, fossil and biogenic.

Fortum Oslo Varme (FOV), the current owner and operator of the WtE plant in Klemetsrud, Oslo, is since 2018 50% owned by Fortum and 50% by the City of Oslo. Earlier, the plant was solely owned and operated by the City of Oslo. FOV WtE plant processes about 400 000 t/MSW per year in 3 lines. The MSW is made of approximately 1/3 household waste, 1/3 commercial & industrial waste and 1/3 refuse derived fuel (RDF) imported from the UK. The plant produces about 700 GWh district heat and 150 GWh electricity per year.

Oslo's ambitious climate goals are the key drivers in the implementation of CCS at the FOV WtE plant. This plant is seen as the ideal candidate for several reasons: (1) it is the largest single point CO_2 emitter in Oslo; (2) more than 50% of the waste is biogenic, and WtE CCS can therefore lead to negative net CO_2 emissions; (3) WtE is a robust, well-established technology that can produce both heat and power, i.e. energy is readily available on-site (at least in the summer time); (4) FOV personnel has a strong industrial know-how; (5) WtE CCS offers a large global potential (high transfer value); (7) the WtE regulatory framework imposes an advanced Flue Gas Treatment (FGT) and hence a rather clean exhaust gas to handle; (8) it is a unique opportunity for Norwegian industry to build competence locally and develop a new "green" business and generate new "green" jobs.

2 Planning and piloting

2.1 OVERALL PROJECT TIMELINE

The project aimed at implementing CCS at FOV WtE plant started in 2015 and has now (March 2021) gone through a series of phases:

- Feasibility study (2015-16)
- First pilot campaign (2016, run by Aker Solutions)
- Concept study (2017)
- Front-end engineering and design (FEED) (08.2018-10.2019)
- Second pilot campaign (02.2019-12.2019)
- Extended FEED/layout update study (11.2019-04.2020)
- Investment decision Fortum (06.2020)
- Final investment decision (FID) on a full-scale CCS value chain was taken by the Norwegian Parliament in January 2021 after proposal from the Government in September 2020, as part of the *Longship* initiative (Longship 2020) that includes Norcem cement plant CO_2 capture plant project and Northern Lights CO_2 transport and storage project (Northern Lights 2020). The FOV CO_2 capture project obtained 50% funding on the condition that it would obtain the remaining funds from other source(s), the main opportunity being offered by the EU Innovation Fund (see also section 3)

The current timeline moving forward is detailed on Figure 1. FOV sent an application to the EU Innovation Fund in October 2020. In March 2021, the EU Innovation Fund announced that the FOV project qualified (as one of 70) to submit a full application by 23 June 2021. The information on the evaluation results from the second stage will be provided in the fourth quarter of 2021. Grants will be awarded in end 2021. If FOV project is awarded a grant, it should be able to start operation in 2026/2027.

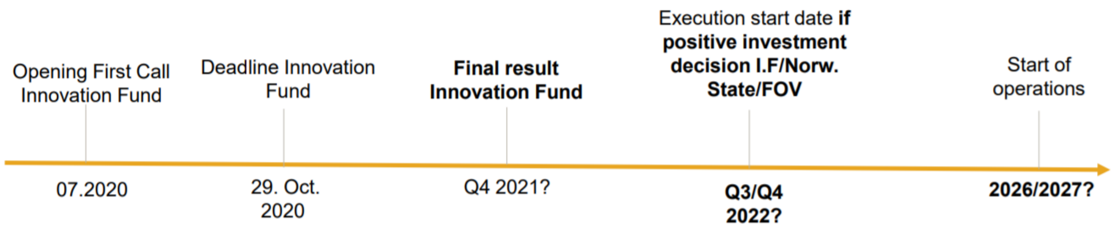

Figure 1. Current timeline for the Fortum Oslo Varme CCS project (picture from FOV)

2.2 CARBON CAPTURE TECHNOLOGY SPECIFICATIONS

The CO_2 capture pilot testing at FOV WtE plant is extensively described and discussed in Fagerlund (2021). Below is a summary of key elements.

2.2.1 Choice of capture technology

The selected capture solution for the FOV WtE CCS project is post-capture using amine (Shell/Cansolv technology). An alternative, the Chilled Ammonia Process (CAP), was considered as well but amine was selected because it is the most advanced and proven technology for large combustion applications, even though experience with WtE is still limited. The potential for a relatively straightforward integration and availability of a wide range of suppliers also helped make it a favoured choice.

As a side note, Oslo also has a second, smaller grate-fired WtE plant (in Haraldrud), operated and owned by the Municipality of Oslo. This plant incinerates ca. 110 000 tons of MSW each year, mainly household waste, and produces district heat. This WtE plant is approaching the end of its economic lifetime and an investment decision concerning its future must be taken within a few years. In this context, oxy-fuel combustion is being considered as a carbon capture technology for this site. Oxy-fuel combustion for mixed waste is a greenfield solution and many challenges remain. A Norwegian pre-FEED project, CapeWaste (IPN project funded by Climit, 2018-2021, REG Oslo project owner), is currently ongoing to assess the feasibility of the concept.

2.2.2 Results from pilot tests

As noted in the timeline in Figure 1, FOV ran a pilot campaign in 2019, the results from which were presented in a webinar in May 2020 and a peer-reviewed scientific publication (Fagerlund 2021). The pilot processed a 0.3% exhaust gas slip stream for a combined duration of over 5000 hours. Extensive analysis work was carried out during the test period which ended in December 2019.

Key data on the flue gas from the 3 lines (K1, K2 and K3 with different flue gas treatment systems) are summarised in Figure 2

Description	Sum K1 & K2	K3
CO_2 amount (t/y)	202 000	258 000
Amount (Nm^3/h)	112 000	132 000
O_2 target level (dry)	7% vol	6%-vol
CO2 content (target O2, dry)	12,2% vol	11,4% vol
H_2O content Winter	18.1% vol	Saturated 35-45°C
H_2O content Summer	18.1% vol	15% vol
Temperature Winter (°C)	80 - 85	85 - 100
Temperature Summer (°C)	110	85 - 100
Pressure (bara)	0.95 - 1.05	0.95 - 1.05

Component	Combined avg. (mg/Nm^3, dry, 11 % O_2)
Dust	2.0
TOC/VOC	0.8
HCl	0.6
CO	18.4
SO2	6.0
NH3	2
NO	50
NO2	1.2
H2S	0.4
Nuclei/cm3	18000
Heavy metals	0.01

Figure 2. Overview of flue gas characteristics from the FOV WtE plant 3 lines (FOV 2020 webinar).

Figure 3 presents a process diagram of the FOV capture plant main elements. In summary, CO_2 capture efficiency was good (90+%) and the CO_2 purity as expected. The pilot campaign did not yield unexpected or alarming results.

Amine-based carbon capture systems can lead to amine (and amine products) emissions to air. It is important to keep track of amine emissions as several are classified as pollutants (SEPA, 2015). As a reference, the BAT-associated emissions levels for NH_3 are 2-10 mg/Nm^3 daily average (JRC, 2019). The median amine emissions to air for the whole testing period were 0.026 ppmv, and the average amine emissions to air were 0.2 ppmv. The average amine emission includes start-up period, self-induced emissions caused by sudden operational changes to test the efficiency of the emission abatement systems, as well as high dust periods, which all led to higher amine emissions.

The amine degradation rate was low. After 2000 hours the degradation had still not exceeded the expected normal operational window (1-2%). The pilot campaign was extended to track degradation rate. The degradation was ca 5% after 5000 hours of operation (Fagerlund 2021). Amine degradation during operation is due to a variety of factors, e.g. heat, CO_2, O_2, NOx & SOx. The mechanisms involved are many, complex and partly unknown (Gouedard, 2012).

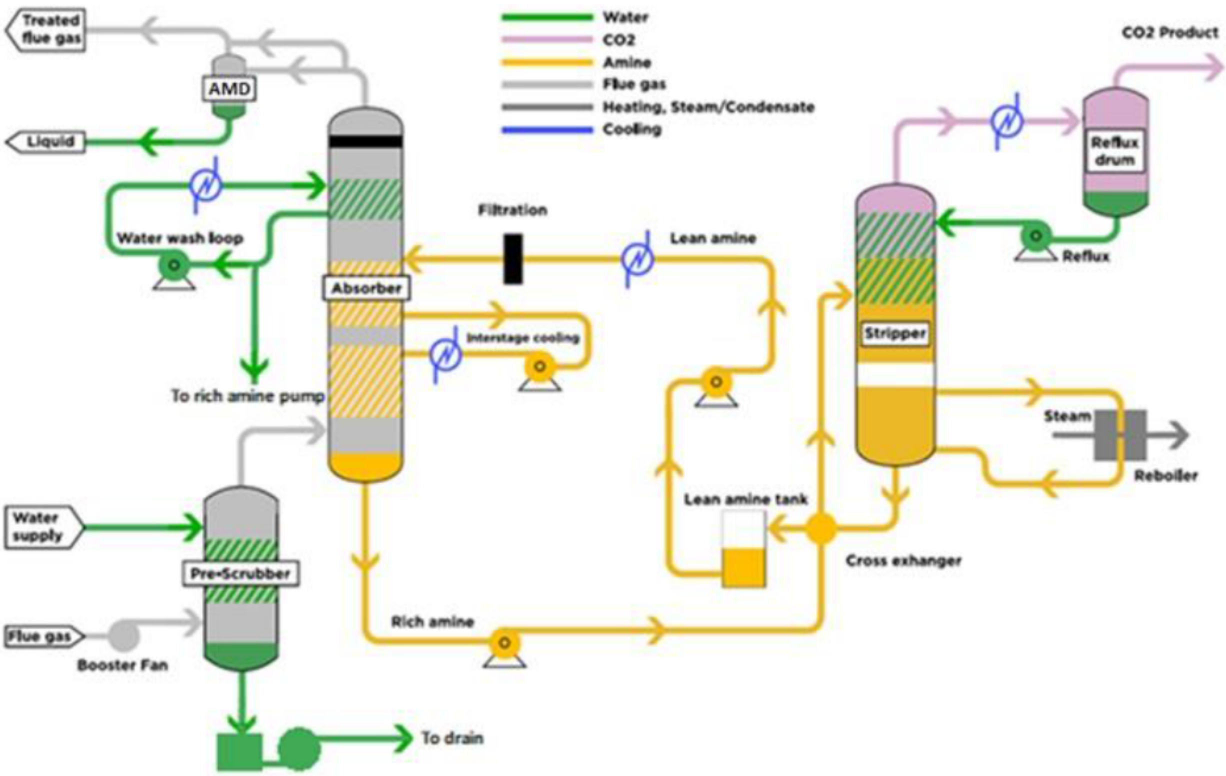

Figure 3. Process diagram of the FOV carbon capture pilot (FOV 2020 webinar). Note: The carbon capture Pilot plant is owned by FOV and was delivered by Kanfa.

3 Moving to deployment?

An indication of the strong momentum surrounding CCS in Norway is that several recent studies have investigated the conditions and characteristics of CCS implementation across different sectors. A few important observations about WtE specifically can be made.

The FOV project has largely been investigated in parallel with the Norcem cement project as one of two possible full-scale CCS sites for the Norway full-scale CCS project. In January 2021, the Norwegian Parliament approved (under the name ***Longship***) the funding of Norcem's CCS project together with Northern Lights (presumably 80-90% of the total costs, i.e. 17.1 billion NOK) while the FOV CCS project will receive 3 billion NOK from the Norwegian authorities on the condition that it is able to raise the remaining funds (ca. 3.8 billion NOK) from other sources, the main possible contributor being the EU Innovation Fund. This may very well postpone the planned 2024 operation start to 2026-2027 (see Figure 1) as the EC funding will be announced in end 2021.

Atkins and Oslo Economics (2020) present the most detailed and exhaustive cost estimates for CCS regarding FOV (and Norcem). These estimates are based on full value chain (FOV and/or Norcem capture + permanent storage), including (1) capture plant(s), (2) compression and conditioning (3) liquefaction, (4) intermediate storage at plant (FOV), (5) transport by trucks to ship terminal/harbour (FOV), (6) intermediate storage at a ship terminal (FOV), (7) ship transport, (8) intermediate storage in Øygarden, and finally (9) pipeline transport to permanent storage in a geological formation ("Aurora") in the North Sea. Table 1 and 2 present the main numbers for the whole value chain different configurations (Norcem + FOV, Norcem only, FOV only).

The largest share of the overall costs (over the first 10 years) is made up by transport and storage. These estimates are close to the ones performed by FOV and Norcem (all figures can be found in the Atkins et al. 2020 report). In terms of comparison between FOV and Norcem, the (CAPEX and OPEX) costs for the FOV capture plant are expected to be somehow higher than for Norcem's. This is due to (1) the FOV plant's location (longer distance to the harbour) and the resulting need for additional intermediate storage and transport to harbour by trucks and (2) the installation of a large heat pump to enable the reuse of the heat into the district heat system. As for the infrastructure related to the transport and storage component of the value chain, the receiving terminal and processing plant for the first phase of the Northern Lights project is dimensioned for 1.5 Mt/y (phase 1) with a 5 Mt/y pipeline. FOV and Norcem will each require a transport and storage capacity of ca. 400 kt/y, leaving available capacity for other interested European actors.

2021 million NOK (VAT not included)	**Norcem capture**	**FOV capture**	**Northern Lights (transport & storage)**
CAPEX – P50	3250	4300	9280
CAPEX – P85	3800	5000	10950
Yearly OPEX – P50	119	223	477
Yearly OPEX – P85	137	254	562

Table 1. CAPEX & OPEX estimates for full-scale CCS. Note: P50 and P85 are statistical confidence levels for an estimate (Data from Atkins & Oslo Economics, 2020).

2021 million NOK (VAT not included)	Norcem capture + Transport + Storage	FOV capture + Transport + Storage	FOV & Norcem capture + Transport + Storage
Total P50	18700	20700	25100
Total P85	20700	22800	27600
Investment framework P50	12900	13900	17100
Investment framework P85	14700	15800	19400
Total OPEX P50	5700	6800	8000
Total OPEX P85	6600	7700	8900

Table 2. Total costs for the different value chain configurations over the first ten years. Note: P50 and P85 are statistical confidence levels for an estimate. Total P50 is approximately {investment + OPEX} but total P85 cannot be summed up in the same manner. (Data from Atkins & Oslo Economics, 2020).

Another study (Kvinge et al. 2019) investigates the costs of CCS for an array of industries in Norway, including WtE. It should be noted that this study applies for "n^{th} of a kind" CCS plants having benefited from extensive know-how and experience from previous plants. The costs of such a plant are expected to be 40% or less of the first-of-a-kind plant. The estimate includes all major elements, i.e. from capture, transport and permanent storage. Kvinge et al (2019) note that for WtE, there will be no need to build a new heat production facility, resulting in a lower CAPEX than for most industries. However, integration challenges and WtE-specific challenges (technical and non-technical) does not appear to be addressed specifically. In terms of costs (2019 NOK), the report estimates that for FOV, the CAPEX will be around 1556 MNOK (ca. 150 million €) and OPEX 211 MNOK /year (ca. 20 million €/year) for ca. 385 kton CO_2/year.

Multiconsult (2019) lists and discusses possible measures to make CCS "profitable" (or economically viable) in different industrial sectors, including WtE. The main conclusion is that whatever the (combination of) measures/incentives (green certificates, CO_2 tax, etc.) to be adopted, there is no silver bullet. Stable political support over several years will be necessary to enable widespread CCS application. Having said that, the opportunities vary between different sectors. For FOV, one straightforward solution could be to add the extra costs of CCS to the waste fee with users/customers paying for this service. Rough estimates show that CCS implementation would increase the annual waste fee by 20-40%, e.g., approximately 750 NOK (approx. 75 €) for a family of four (Stuen 2019).

Finally, the socio-economic impacts of the implementation of CCS are also important to consider as they put the project into a broader perspective than the purely economic one. This enables an overview of the benefits and shortcomings in a multi-faceted, international context. Aarrestad & Viumdal (2020) summarise and evaluate important aspects given two different possible scenarios: (1) The current European Climate policies (i.e. 80% CO_2 reduction by 2050) and 2) the Paris Climate agreement (central aim: keeping a global temperature rise this century well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 °C) for the different configurations (FOV only, Norcem only and both). The largest socio-economic impact is the full-scale demonstration of CCS as a safe climate measure, followed by the utilisation of Norway's geological and gas resources.

In terms of policy, even though Norway has had a leading position in the development and demonstration of CCS (capture, transport, sequestration), it seems clear that the EU should take a strong role when it comes to policy and economic support initiatives for CCS deployment, including incentivizing negative emissions. This is needed to develop a legal framework and sound economic basis to accelerate implementation in several countries.

Moreover, challenges pertaining to questions of local regulations and stakeholder acceptance should also be considered. For example, The FOV WtE plant is located in a densely populated area and this requires special care concerning emissions/dispersion, transport, area footprint and NIMBY questions. In addition, one could expect time-consuming regulatory obstacles when implementing a full-scale WtE + CCS plant for the first time.

Regardless, it should be mentioned that other Norwegian WtE actors have started **CCS/CCUS initiatives** since 2019-2020. Most of these activities are at an early stage of development, e.g., feasibility studies, but some examples include BiR WtE plant in Bergen, Returkraft WtE plant in Kristiansand, Forus WtE plant in Stavanger, Borg CO_2 in Øra and Statkraft Varme WtE plant in Trondheim. Several of these actors have come together to establish a Scandinavian CCS alliance (together with Copenhagen & Stockholm) to exchange knowledge and experience.

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