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Renewable energy supply concepts for next generation cities using the integrated urban modeling platform INSEL 4D

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Abstract

To decarbonize the urban energy system, a maximum amount of renewable energy generation is crucial in addition to demand reduction strategies. Depending on the density of urban areas, the contribution of local renewable energy generation varies. It is still an open question whether local or regional renewable generation or import from further locations has the best cost and life cycle performance. To model such scenarios, an urban data management and modeling platform is under development to provide a software infrastructure for smart and sustainable city planning and operation. Today such platforms are mostly designed to handle and analyze large urban data sets from very different domains. Modeling and optimization is usually not part of the software concepts. However, such functionalities are considered crucial for transformation scenario development and optimized smart city operation.

The paper discusses the required software architecture concepts for energy demand and renewable energy generation modeling. The main driver is to derive zero carbon strategies for cities while including all major sectors of CO2 generation. The platform needs to handle multiple scales in the time and spatial domain, ranging from long term population and land use change to hourly or sub-hourly matching of renewable energy supply and urban energy demand.

The methodology and software concepts are applied to the case study district Brooklyn Borough Hall in New York. Based on the building energy demand modeled from the 3D city geometry, various renewable energy supply scenarios are simulated. The results show that 80 percent of the building heating and cooling demand can be covered by local and nearby renewables at double the cost of today´s electricity.

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1. Introduction

To support the planning and operation of renewable supply systems for cities with a minimized CO2 footprint is a huge challenge, as very different domain knowledge needs to be combined in an urban platform. Urban platforms mostly consist of urban data collection and analysis from very diverse sources such as sensors, municipal data records, knowledge repositories or social media streams (Psyllidis et al., 2015).

Model based predictions can help to compare different energy system operation scenarios and schedules and help to approach the optimum strategy for minimized CO2 emissions and costs. Also medium to long term scenarios of urban development cannot be derived from data alone, as this would most likely result in business as usual. To transform cities to a zero carbon future, very ambitious and disruptive changes need to take place, which cannot follow the trends given by today´s urban data.

To develop such zero carbon transformation strategies for complex urban systems, we propose to model the buildings, energy supply and distribution systems, transport, food and water infrastructure of a city, calibrate the model with urban monitoring data and then to simulate transformation scenarios towards zero carbon cities. The models can also be used for optimize today´s infrastructure performance. We also suggest to extent urban data platforms to integrated data and modeling platforms, which combine data analysis and model based scenario development. The front end and visualization features should give access and involve citizens and local stakeholders interacting both in operation and strategic planning for sustainable cities.

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2. Renewable energy system modeling

The renewable energy system modelling described here is based on the simulation framework INSEL (www.insel.eu). A workflow management system called Simstadt is used to process geometry data and parametrize the simulation models. To calculate heating and cooling demand, 3D CityGML models are used that include further building information (height, roof type), usage and age. Those models can be scaled up to the size of whole cities (Nouvel et al., 2015). In addition to the 3D city model, further data collection (and management) is required to analyse the overall energy balances. Various sources, such as land register data and data from surveys of the research team, are tapped. This leads to a database that includes public, residential and commercial buildings in terms of building characteristics (year of construction, energy systems, energy consumption, heating, ventilation and air conditioning) and insulation standards.

Within this work, the heat demand calculation was first carried out on a monthly basis according to specific norms but is then scaled down to hourly time steps. Utilizing dedicated algorithms (Romero et al, 2017), the roof area suitable for PV systems is determined. This area, the specific orientation and optimal tilt is then used for detailed annual PV yield calculations, also on an hourly basis. The PV modules are represented by a two diode model that is parameterized according to state of the art modules. In our case study, we used a validated PV system model. This approach also includes the inverter system and a MPP tracking loop. All simulations are carried out by the simulation engine INSEL (Integrated Simulation Environment Language). Wind turbines with different power range are modeled by characteristic curves model based on data provided by the manufacturer. The potential for small wind turbines is calculated using the 3D CityGML building model combined with available wind data. Here the assumption was used to only mount wind turbines on the north oriented roof side to avoid an impact on PV generation. The potential for large scale off shore wind turbines is derived from available New York City wind potential analysis. The meteorological data (global radiation, wind speed, ambient temperature) is taken from public available sources.

3. Case study

The modelling approach was applied to a case study in the New York City district Borough Hall, where all the buildings in the district were simulated that are connected to a single substation with hourly resolved electricity monitoring data. From a total population of 244,920 persons in the district, 147,129 persons receive electricity from the monitored substation and live in 71,378 households. In total, there are 11,614 buildings connected (and modeled), of which 7780 are residential and 2029 mixed use and 1,805 buildings non-residential. The mean income in the district is 140,580 US dollar annually and the average age 35,7 years.
The measured electrical energy use at the substation is 1,336 GWh per annum.

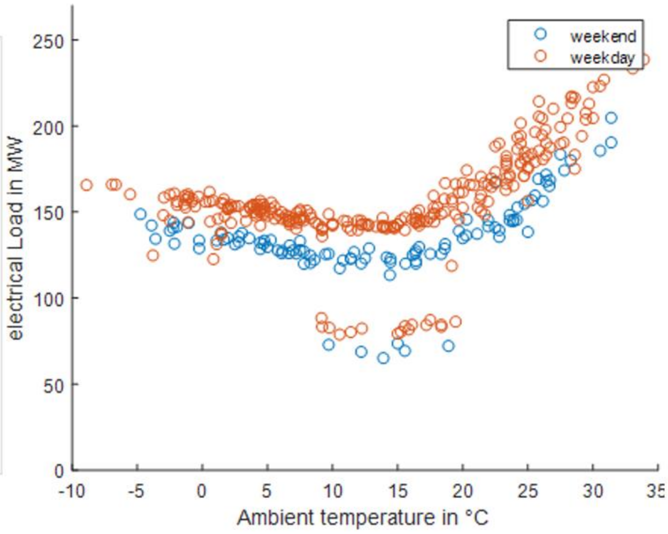


Figure 1: measured electrical load of all buildings connected to the Borough Hall substation.

The first analysis is to assess the energy and CO2 emission status quo of the district under investigation. The aforementioned data sources were analysed to find useful information concerning energy demand or energy systems and infrastructure.

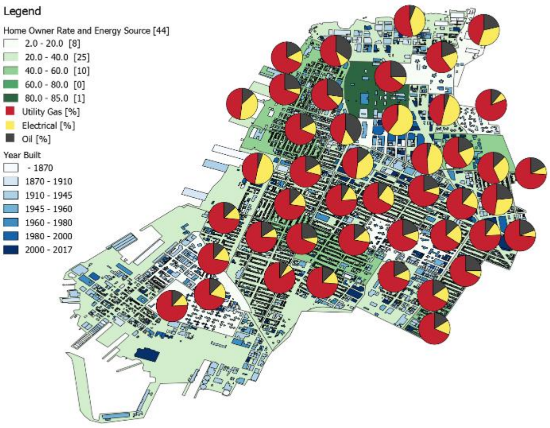


Figure 2: Home owner rate, energy source, fuel type distribution and year built in Borough Hall

Figure 1 shows the share of fuel types used for heating in each of the census tracts inside the Borough Hall case study district as pie charts. In most of the tracts, utility gas is dominating, however there are some tracts that have a significant share of electrical heating, a few are even dominated by oil. Another important information is the type of heating system in the buildings, e.g. if it is a central or decentral system, which can partly be deduced from the fuel type. It is more probable that buildings with electrical resistance heating install heat pumps fed by renewable electricity compared to an existing central heating system with gas. Electrical heating is predominant in newer office buildings in Downtown Brooklyn (upper right part of Fig. 2). Also visible in Fig 2 is the year built of the buildings in blue and the ratio of house owners in each census tract district (green). Different strategies to stimulate the desired modernizations could be applied, depending on this information.

The heating and cooling demand was modeled for every individual building in the district, based on the building age and using the urban geometry and building physics and usage data from different New York city reports on building performance. The three-dimensional (3-D) building massing model of New York City is provided online from DOITT in the CityGML format ([https://www1.nyc.gov/site/doitt/ initiatives/3d-building.page](https://www1.nyc.gov/site/doitt/initiatives/3d-building.page)). This dataset is later on converted to 3D Tile format as a service with the OGC 3D Portrayal Service standard implemented by the Fraunhofer Institute (Reference: OGC Testbed 13 ER). This service allows users and developers to request and interact online with the 3D building dataset.

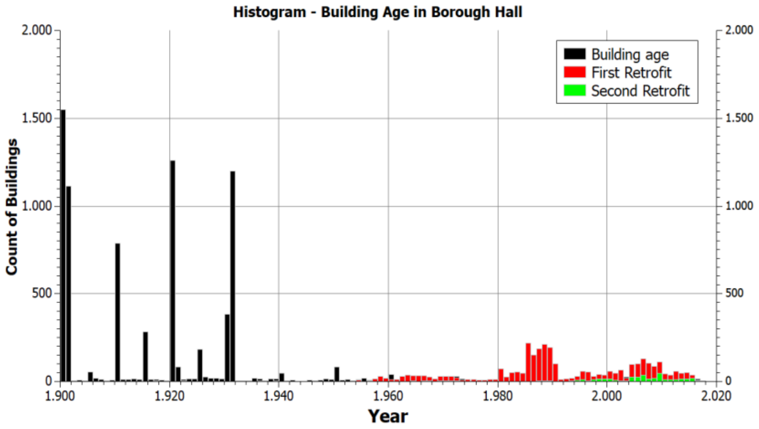


Figure 3: distribution of building ages in the district

In total the heating demand of all buildings simulated adds to 1,588 GWh per year.

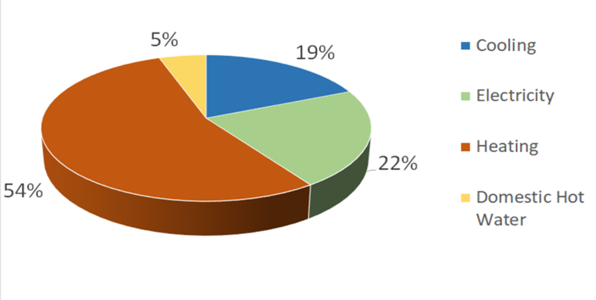


Figure 4: Distribution of energy demand in the analyzed district

Figure 5: Visualisation of calculated heating demand in Brooklyn case study using 3D CityGML models

The simulation model then allows to calculate efficiency scenarios, for example increasing the cooling temperature setpoint and reducing infiltration losses. The demand simulation results serve as an input to the renewable supply system simulation.

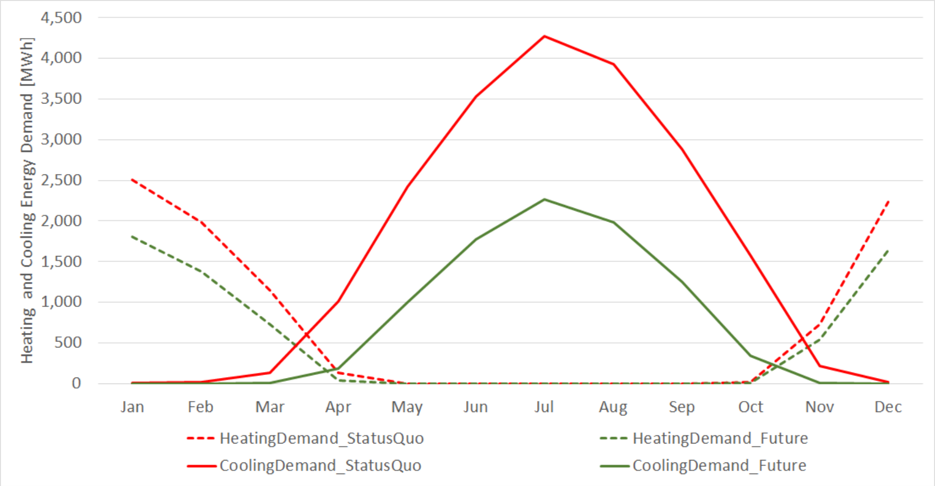


Figure 6: Cooling demand reduction of 56% by increasing temperature setpoints by 6 K and reducing infiltration losses, which also decreases the heating demand by 19%.

The current electricity generation mix, which supplies the district is made up of less than 6% renewable energy sources (RES) and has a CO2 footprint of 4.2 t CO2eq per capita.

The Brooklyn Borough Hall Case Study goals are 100% RES electricity mix and 1.4 t CO2eq/cp (NYC government roadmap).

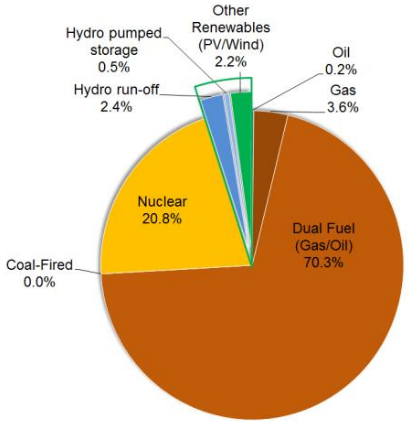


Figure 7: electrictiy generation mix supplying the Borough Hall substation (NYISO).

4. Results

Within this work, the following different scenarios were examined: *S1: Status quo, S2: Electrification of heating, S3: Building refurbishment efficiency scenario, S4: Efficiency with large scale renewable energy generation.* The scenarios from S1 to S3 were developed to analyze various building stock electricity needs.

The sizing of the renewable generation for the first three scenarios was done using the electricity demand profile of Borough Hall District (2013) as the status quo scenario S1, considering heat pumps installation for 75% of the buildings in scenario 2, including building efficiency measures and the electrification of the taxi sector in scenario 3. Scenario 4 then uses a higher photovoltaic contribution as scenario 3.

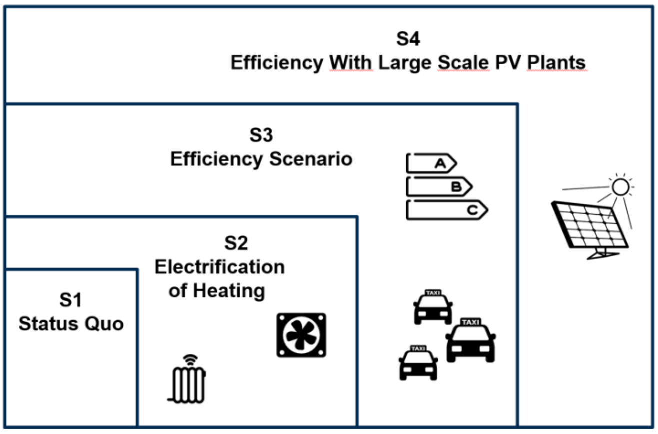
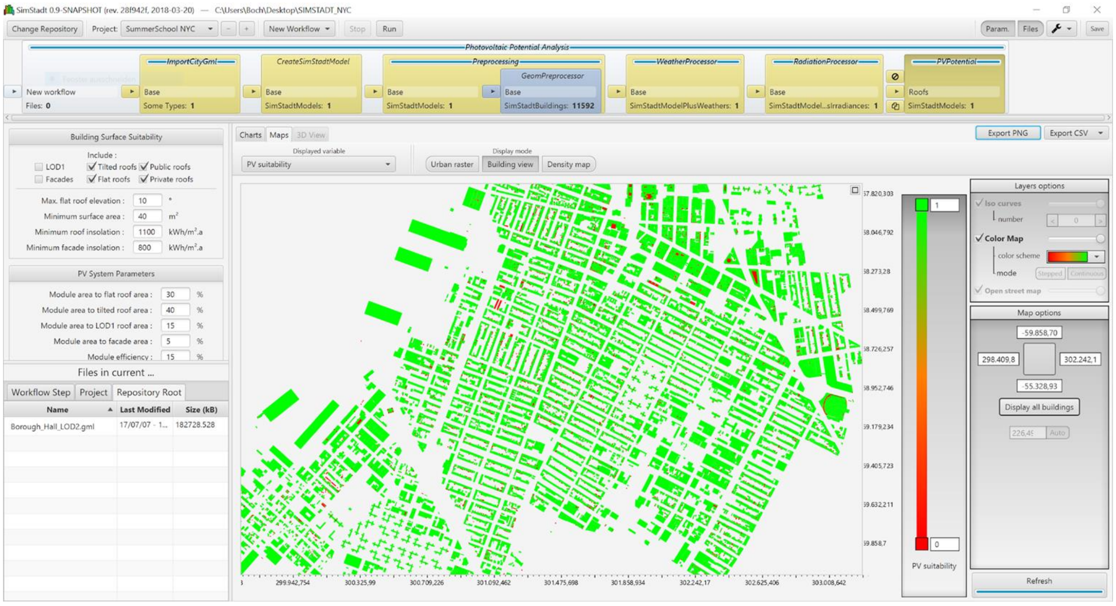


Figure 8: Scenarios considered in the work.

First of all the economic photovoltaic potential was calculated, which is assumed to be achievable for roofs that have an annual solar irradiance of 1100 kWh/m2 or higher.



Project: SummerSchool NYC

New workflow
Files: 0

Base
Some Types: 1

SimStadtModels: 1

SimStadtBuildings: 11592

SimStadtModelPlusWeathers: 1

SimStadtModel...sIrradiances: 1

Roofs
SimStadtModels: 1

Building Surface Suitability

Include :
☐ LOD1 ☑ Tilted roofs ☑ Public roofs
☐ Facades ☑ Flat roofs ☑ Private roofs

Max. flat roof elevation : 10 °
Minimum surface area : 40 m²
Minimum roof insolation : 1100 kWh/m².a
Minimum facade insolation : 800 kWh/m².a

PV System Parameters

Module area to flat roof area : 30 %
Module area to tilted roof area : 40 %
Module area to LOD1 roof area : 15 %
Module area to facade area : 5 %
Module efficiency : 15 %

Files in current ...

Workflow Step | Project | Repository Root

Name	Last Modified	Size (kB)
Borough_Hall_LOD2.gml	17/07/07 - 1...	182728.528

Displayed variable: PV suitability

Figure 9: Modeling of the roof and facade photovoltaic energy generation potential.

For the given total electricity consumption of 1.33 TWh (scenario 1 status quo), the roof PV could cover 29.4%. The rest could be covered by on- and offshore wind.

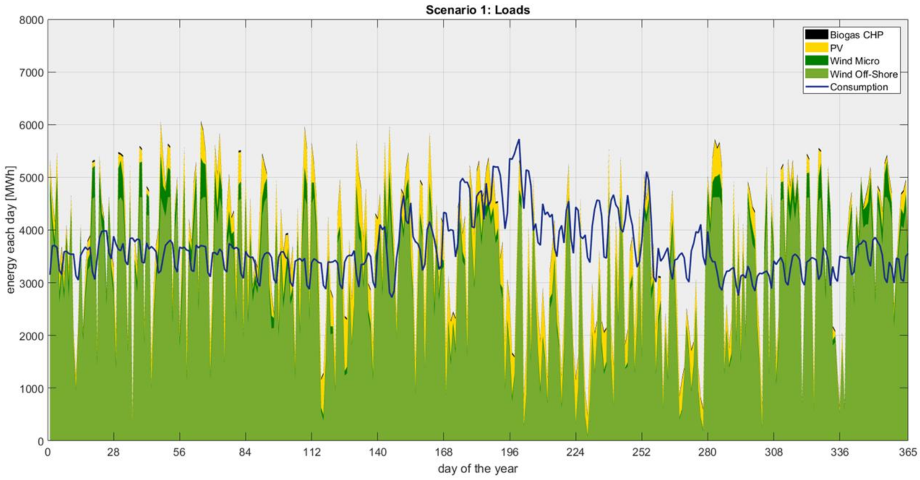


Figure 10: covering the loads of the status quo situation with PV and wind.

Up to 42 GWh of electrical storage would be required for a 100% renewable supply without imports. and electricity prices would rise up to 1.41 $/kWh to reach an overall emission goal of 1.3 tons CO2/a. If the storage volume is decreased for example to 3.8 GWh, 84% of the total demand could still be directly covered and the costs would reduce to 0.42 $/kWh.

The electrification of the heating demand would strongly increase the winter electricity demand (scenario 2).

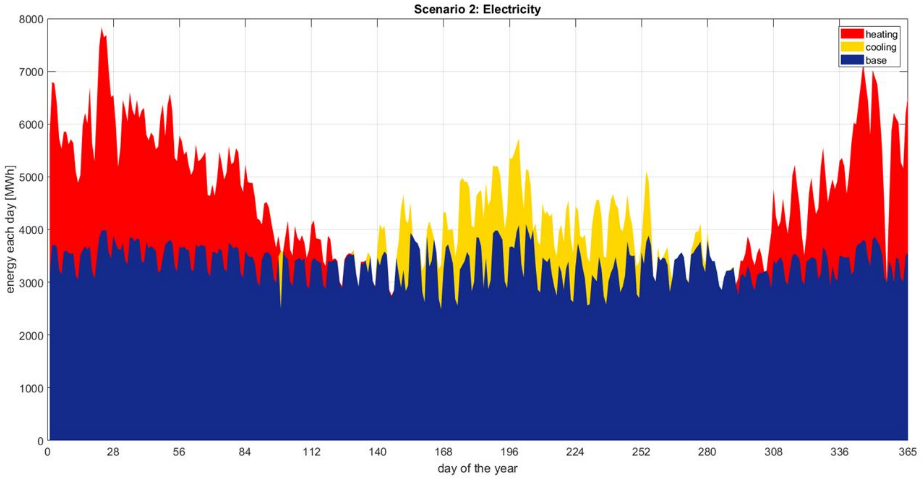


Figure 11: Electricity demand including electrification of the heating sector with heat pumps.

Both storage size and electricity costs would increase up to 69 GWh for a 100% renewable scenario and 2.13 $/kWh with a better CO2 balance of 0.6 tons CO2/a. Storage size reduction to 5.6 GWh would still provide 84% renewable coverage at a cost of 0.5$/kWh.

The efficiency scenario would strongly reduce demand to 0.61 TWh, including 0.16 TWh for heating and 0.05 TWh for cooling. The taxi electrification would mean an additional electricity demand of 0.001 TWh.

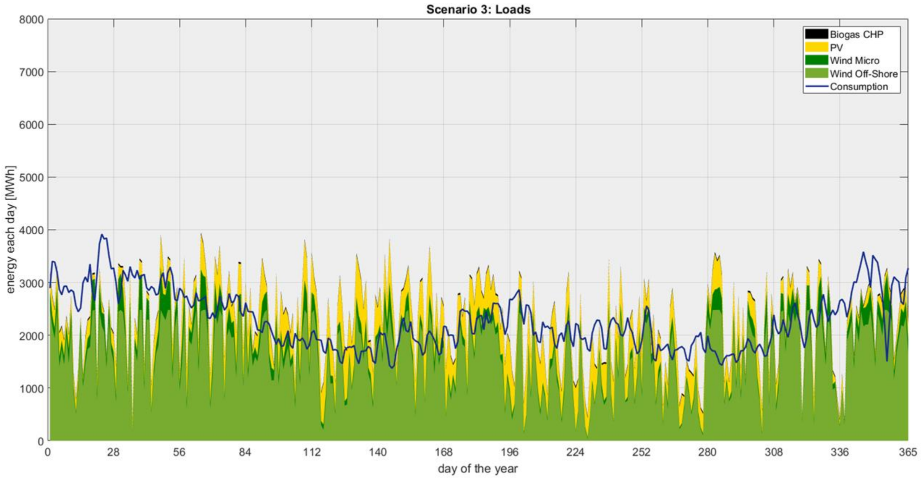


Figure 12: Load demand and renewable supply for the efficiency scenario

Due to the lower demand, the roof PV systems could now cover 37%.

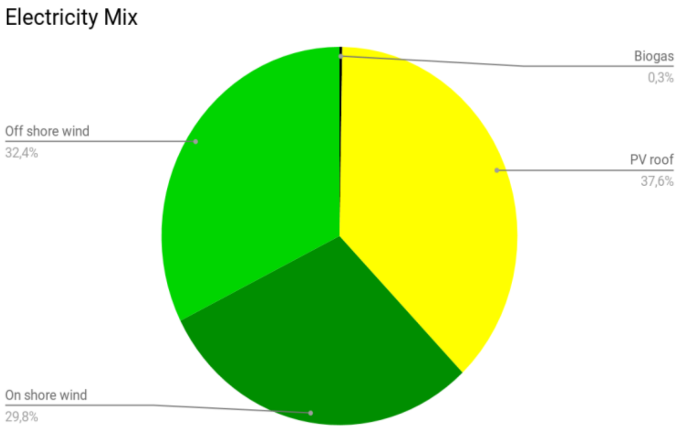


Figure 13: Electricity mix in the efficiency scenario.

The efficiency scenario results in the lowest emissions of 0.26 t CO2eq per capita at electricity prices between 0.26 and 1.92 $/kWh depending on storage size between 0 and 38 GWh. For a storage volume of 2.7 GWh, 85.4% of the demand could be covered at a cost of 0.33 $/kWh.

In scenario 4, the contribution of offshore wind turbines is limited to 20 units and the rest is provided by large photovoltaic plants. The demand contains all efficiency measures used in scenario 3.

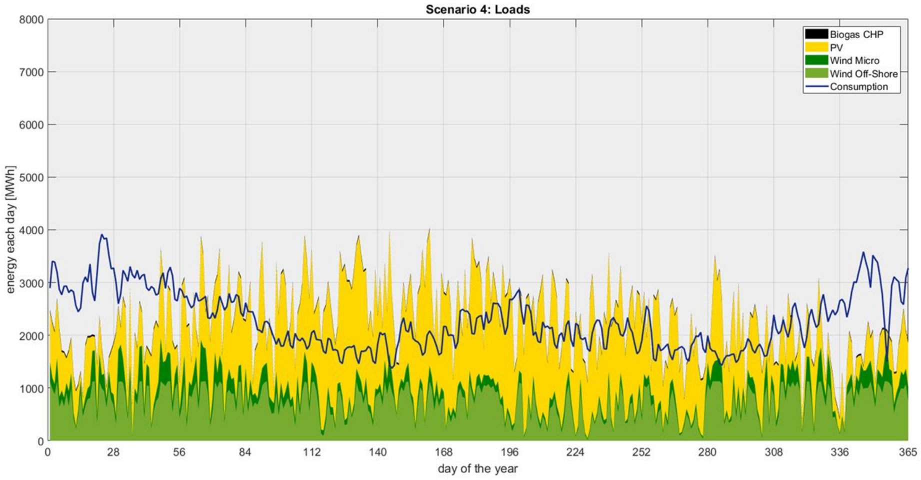


Figure 14: Scenario 4 with limited offshore wind capacity and large PV power plants. Annual electrical demand and production on a daily base (scenario electrified heating and efficiency with large scale PV, CHP, small building integrated and large off shore wind energy plants)

Now photovoltaic generation dominates the energy mix. The electricity price varies between 0.33 and 2.04 $/kWh for storage sizes between 0 and 64,9 GWh. The emissions are at 0.35 t CO2eq/cp. 83% of renewable generation can be achieved for a storage volume of 2.8 GWh at costs of 0.44$/kWh.

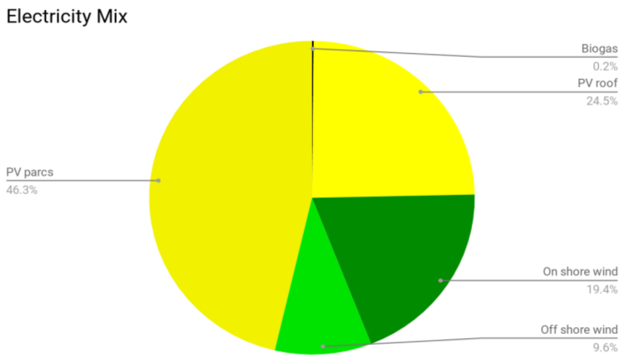


Figure 15: Distribution of renewable generation of the total energy mix.

The results of all four scenarios are summarized in the following table.

	S1: Status Quo	S2: Electrification of Heating	S3: Efficiency	S4: Efficiency with PV Plants
Demand	1.2 TWh	1.2 TWh	0.61 TWh	0.61 TWh
Heating	-	0.3 TWh	0.16 TWh	0.16 TWh
Cooling	0.1 TWh	0.1 TWh	0.05 TWh	0.05 TWh
Taxi electrification	-	-	0.001 TWh	0.001 TWh
Storage Size	0-42,6 GWh	0-69 GWh	0-38 GWh	0-64,9 GWh
Electricity price	0.32-1.41 $/kWh	0.36-2.13 $/kWh	0.26-1.92 $/kWh	0.33-2.04 $/kWh
Emissions in t CO2eq/cp	1.3	0.61	0.26	0.35
Yearly RES	100%	100%	100%	100%
Daily RES autonomy, required storage, resulting electricity price	83.95%, 3.8 GWh storage, 0.42 $/kWh	84.15%, 5.6 GWh storage, 0.50 $/kWh	85.38%, 2.7 GWh storage, 0.33 $/kWh	82.96%, 2.8 GWh storage, 0.44 $/kWh

Table 1: Summary of results for the four scenarios.

The results here show that an 80 to 85 % renewable energy scenario is realizable with small to medium sized electricity storage solutions at approximately twice the current electricity cost. A 100% renewable scenario would drastically increase the electricity price with the main cost driver being the needed storage size. This work shows that even in dense urban areas such as New York, very ambitious CO2 emission reduction goals can be reached with renewable energy generation for an efficiently refurbished building stock, even for an electrified heating sector. The costs mainly depend on storage options.

5. References

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Psyllidis, A., Bozzon, A., Bocconi, S., & Bolivar, C. T. (2015). A Platform for Urban Analytics and Semantic Data Integration in City Planning, 21–36. http://doi.org/10.1007/978-3-662-47386-3

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