Net Zero Energy Districts:
Connected intelligence for transition to carbon-neutral cities

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- ***The importance*** of transition of city districts to **self-sufficient NZEDs** is very high, as it would greatly decentralize and multiply efforts for carbon-neutral cities.
- We propose a ***model to assess the feasibility of transition*** of city districts to self-sufficient Net-Zero Energy Districts, based on locally produced renewable energy.

Contents

1. Introduction: Problem definition

Net Zero Energy Districts (NZED) are city districts in which the **annual amount of CO2** emissions released minus of emissions removed from the atmosphere is zero (or negative).

NZEDs constitute a major component of a new generation of **“smart-green cities”** that combine **smart city technologies** & **renewable energy technologies**.

NZEDs promote environmental sustainability they contribute to cleaner environments and can address threats and disasters related to climate change. These are top conditions of quality of life in cities.

The aim of the paper is to

(a) assess the **feasibility of transition** of city districts to NZEDs **based on local renewable energy,** which would decentralise and strengthen the transition to carbon neutral cities

(b) **identify thresholds**, which allow for a housing district to become a self-sufficient NZED, covering all energy needs by locally produced RE.

1. Introduction: Hypotheses

H1: It is feasible to design an NZED relying on locally produced renewable energy

There is evidence that renewable energy systems (geothermal, wind, solar, biomass, waste) can cover most energy needs of a city, and if combined they can cover the entire city's demand for energy.

Based on this evidence, our first hypothesis is that a combination of three types of transition measures can lead to NZEDs (a) **smart systems** for energy saving and optimisation, both for housing and mobility, (b) **locally produced RE mainly from photovoltaic panels** (excluding wind and biomass), and (c) nature-based **solutions** for CO2 removal.

H2: There are thresholds that limit the feasibility of NZEDs

Under certain **thresholds** of population density, per capita energy usage, local RE deployment, and nature-based solution, a housing district can evolve to NZED.

NZED is based on the **balance** between energy consumption / CO2 emissions and renewable energy / CO2 capture.

H2 wants to define the **conditions and thresholds of this balance and identify interdependencies** among the various components of carbon neutrality, such as energy usage, RE, and CO2 capture.

H3: The compact city principle is not compatible with NZEDs relying on locally produced RE

In the 1990s the principles of 'Smart Urban Growth', 'Compact City', 'New Urbanism', 'Transit-Oriented-Development' and 'LEED for Neighborhood Development' converged to a coherent model for the sustainable design of city districts.

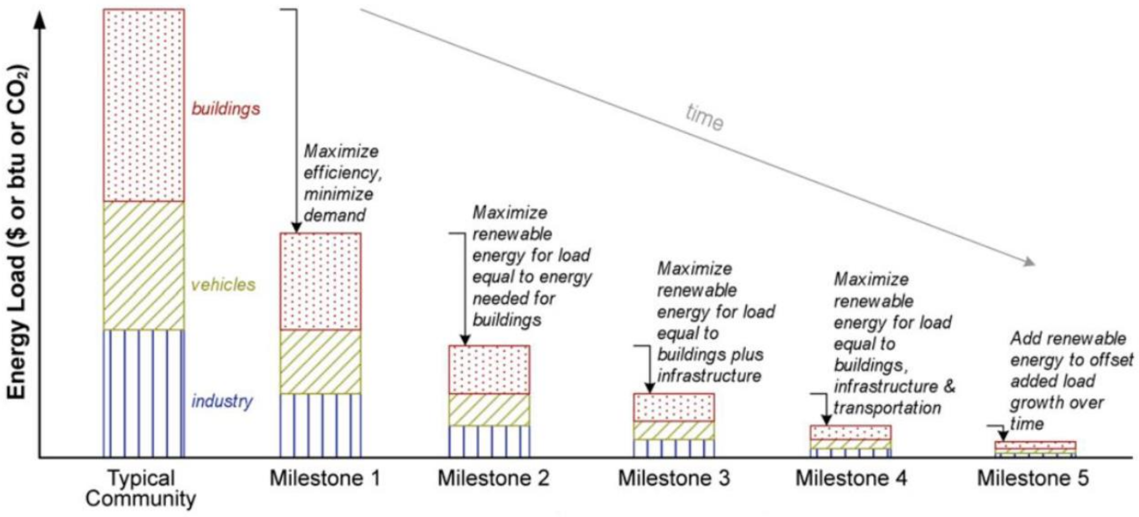
The core of the model is the compact city principle of high population density, location close to existing city boundaries, brownfield areas renewal.

H3 questions the **validity of the compact city mode**l under net-zero and fully locally produced renewable energy

1. Introduction: Theoretical framework, 2 perspectives

(a). **Previous work on the making and operation of ZNEDs:**

- Maximising efficiency +
- Maximize renewable energy per sector

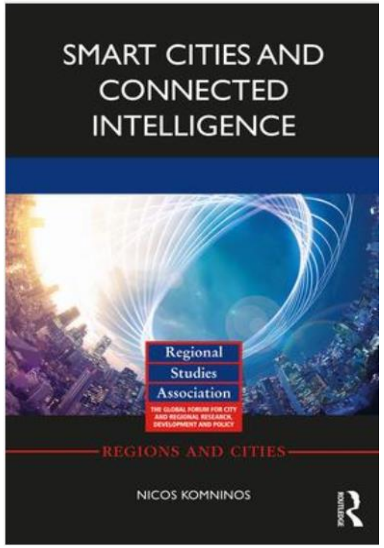


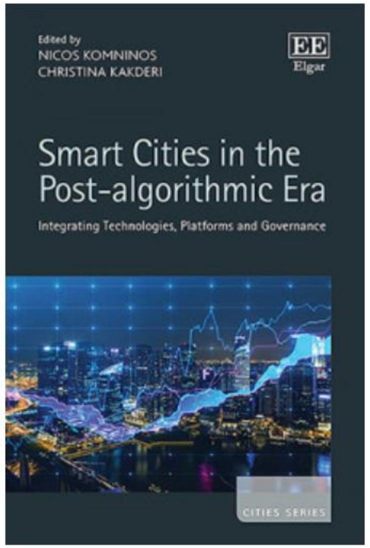
Source: Carlisle, N., Van Geet, O., & Pless, S. (2009)

(b). **Connected intelligence perspective**

Combine all **available capabilities** in a district. Capabilities in

- **Technologies,** smart systems, renewable energy
- **Rules and institutions**, energy communities, energy sharing, green building codes, planning
- **Human behaviour** for saving energy, investing in environmentally friendly solutions

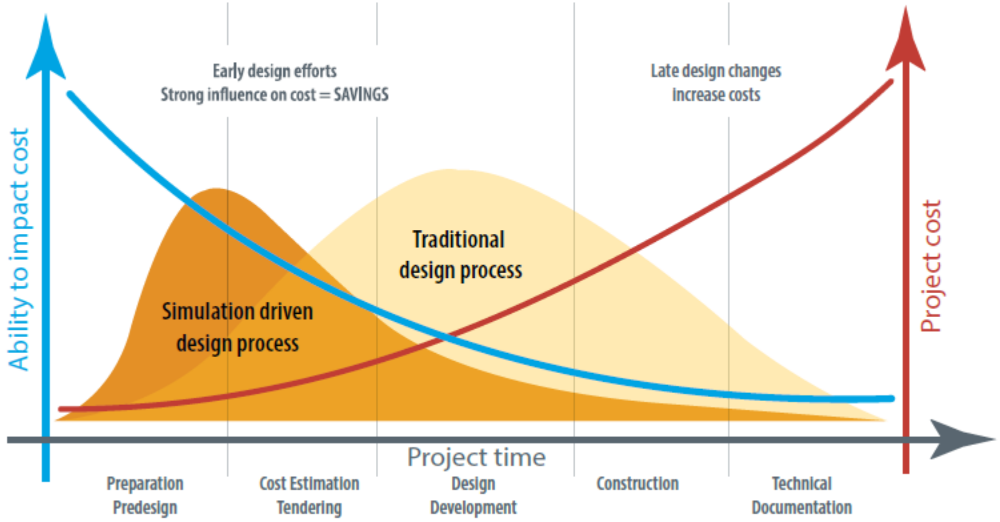




1. Introduction: Methodology and data

The methodology we follow to verify or reject the hypotheses H1, H2, H3, combines literature review, model design, model feed with statistical data, and a large number of simulations to assess the outcome of the model in various climate, social, and district settings.

- St1: We start with a **literature review** on the typology and processes in an NZED
- St2: Using this literature, **we define the building blocks and variables of a model** for transition to NZED
- St3: We work on **statistics to provide data to the model** that allows the transition to NZED to be evaluated under different conditions.
- St4: **Model simulations**. We define the baseline model. Then, we run the model under different conditions to understand the process towards zeroing CO2.
- St5: **Assessment of hypotheses** H1, H2, and H3 and **conclusion.**



2. NZED literature highlights that drive the design of model

Origins of the NZED concept

The origin of the Net Zero Energy District concept can be found in the literature on '**Net Zero Energy Buildings**'. These are buildings that are energy neutral and deliver to the energy grid as much energy they drawback.

Moving from the level of building to city district or community, the concept changes substantially as **the district is more complex than the building** and consumes energy not only for buildings but also for industrial activities, public spaces, and an array of infrastructures.

Types of net zero districts

Zero Energy Districts focus on new constructions and have similar objectives compared to NZEDs

Positive Energy Districts focus net zero + energy import-export between city districts

Net Zero Energy Communities, the focus is the community and user engagement. They may also refer to spatial entities that may be larger of city districts or located in rural areas.

Clean Energy Communities *are* formed to achieve specific goals of cleaner energy production, consumption, supply, and distribution.

Processes towards carbon neutrality

Emissions inventories to monitor, record, analyse urban emissions, and increase user awareness.

Renewable energy *production* is the fundamental mode towards carbon neutrality.

Smart grid and smart meters modernize the energy network adding new functionalities of user-producer coordination and load optimisation.

Smart home systems for energy saving and optimisation through automation.

Nature-based *solutions* to remove CO2 emissions from the atmosphere.

3. A model for transition to NZEDs: Building blocks

Block A. District

Demographics
- Population
- Number of households
- Density

Land use
- Total area of the district
- Housing area
- Social care, education, culture, sports area
- Local retail and services area
- Road and parking area
- Green, gardens, urban forests area

City grid
- Number of building blocks on the grid
- Number of lighting poles on the grid
- Road length of the district grid

Building code
- Building Coverage Ratio
- Floor-Area Ratio
- Housing floor per capita
- Number of building floors

Mobility
- Number of commuting travels
- Average distance per commuting travel
- People using private car in commuting
- People using public transport in commuting-
- People using bicycle or work from home

Block C. Measures towards NZED

C1. Housing: energy efficiency by refurbishment
C2: Housing: energy saving by smart home solutions
C3. Public lighting: saving by smart systems
C4. Transport: green mobility & energy saving
C5. Smart grid and storage
C6. Local RE: Photovoltaic panels
C7. Local RE: Geothermal
C8. Nature-based solutions: Tree canopy

Block B. Energy usage & CO2

Energy consumption residential
- Energy consumption residential, total
- Energy consumption residential-Heating
- Energy consumption residential-Lighting & appliances
- Energy consumption residential-Domestic water heating
- Energy consumption residential-Cooking
- Energy consumption residential-Cooling
- Energy production renewable

C02 emissions residential, total
CO2 emissions per category of usage

Energy consumption streetlighting
- Total
- Lamp power per pole
- Street lighting system operating hours per year

Energy consumption in mobility
- Energy consumption in mobility by public transport
- Energy consumption in mobility by private car
- Energy consumption in mobility by electric car & micro-mobility

- CO2 emissions in mobility by public transport
- CO2 emissions in mobility by private car

Block D: Balancing energy and CO2

Energy	Residential energy saving	Mobility energy saving	Smart grid, storage, renewable energy
ΣE_B	Esav [C1 +C2]	Esav [C3+C4]	E_{RES} [C5+C6+C7]

CO2	Green mobility	Nature-based solutions
ΣC_{MOB}	-CO2 [C4]	-CO2 [C8]

3. Block A. District features

Block A. District: Describes the physical features of a housing district, in terms of population, density, land use, buildings, open spaces, transportation, planning regulations and codes that shape a city district.

Block A includes 22 variables

Code	Name	Measurement unit
	Demographics	
P	Population	Physical person
AP	Active population as % of the district population	Working person
H	Number of households	Household
D	Density	Persons/Hectare
	Land use	
At	Total area of the district	Hectare
Ah	Housing area	Hectare
As	Social care, education, culture, sports area	Hectare
Ar	Local retail and services area	Hectare
Ar	Road and parking area	Hectare
Ag	Green, gardens, urban forests area	Hectare
	City grid and public lighting	
Bb	Number of building blocks on the grid	Building block
Pl	Number of lighting poles on the grid	Pole
Rlg	Road length of the district grid	Kilometer
	Building code	
BRC	Building Coverage Ratio	Percentage
FAR	Floor-Area Ratio	Number
Hfpc	Housing floor per capita	Square meter
Bnf	Number of building floors	Floor
	Mobility	
Tpc	Number of commuting travels per worker per year	Travel
Dtpc	Average distance per commuting travel	Kilometer
Pmpc	People using private car in commuting-% of total	Percentage
Pmpt	People using public transport in commuting- % of total	Percentage
Pmgr	People using bicycle, walk, or work from home-% of total	Percentage

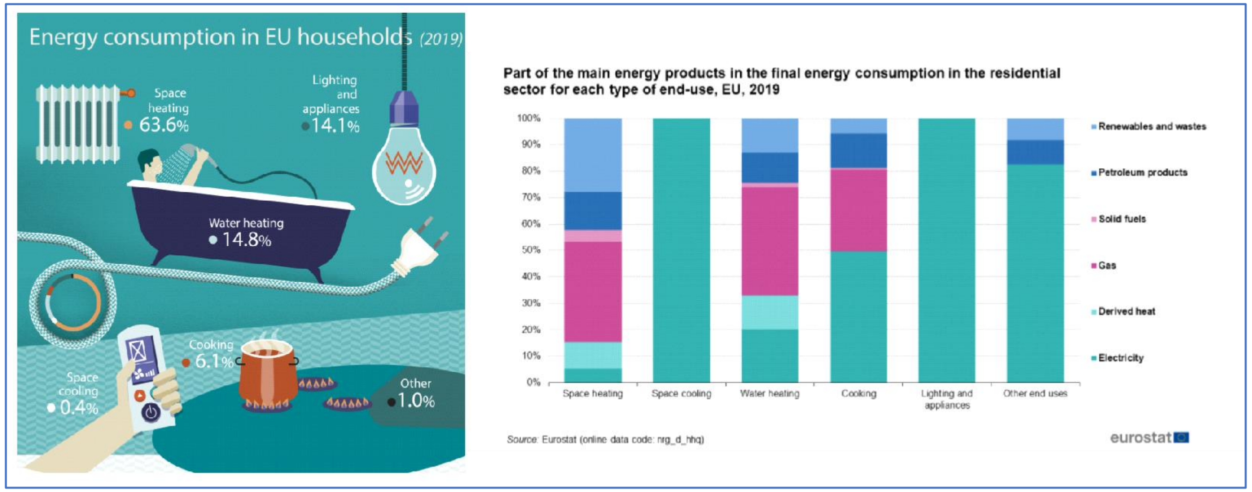
BRC: ratio of the building floor area divided by the land (site) area

FAR: ratio of a building's total floor area (in all floors) to the size of the land upon which it is built

3. Block B. Energy consumption and CO2 emissions

B. Energy usage and CO2 emissions: Comprises 23 variables of energy usage and CO2 that change with respect to climate conditions, socio-economics of the district, energy consumption per capita, and others.

With respect to variables of block A defines the residential, public space, and mobility energy consumption.



Code	Name	Measurement unit
ERPC	Energy consumption residential per capita	kWh/year
ERT	Energy consumption residential, total	kWh/year
EH	Energy consumption residential-Heating	Per cent of total
ELA	Energy consumption residential-Lighting & appliances	Per cent of total
EDWH	Energy consumption residential-Domestic water heating	Per cent of total
EC	Energy consumption residential-Cooking	Per cent of total
ECL	Energy consumption residential-Cooling	Per cent of total
ERE	Energy production renewable	kWh/year
CRT	C02 emissions residential, total	Tons/year
CH	C02 emissions residential-Heating	Tons/year
CLA	C02 emissions residential-Lighting and appliances	Tons/year
CDWH	C02 emissions residential-Domestic water heating	Tons/year
CC	C02 emissions residential-Cooking	Tons/year
CCL	C02 emissions residential -Cooling	Tons/year
ESL	Energy consumption streetlighting, total	kWh/year
Lp	Lamp power per pole	Kwh
HSL	Street lighting system operating hours per year	Hours
EM	Energy consumption in mobility, total	kWh/year
EMPT	Energy consumption in mobility by public transport	kWh/year
EMPC	Energy consumption in mobility by private car	kWh/year
EMEV	Energy consumption in mobility by electric car & micro-mobility	kWh/year
CMPT	CO2 emissions in mobility by public transport	Tons/year
CMPC	CO2 emissions in mobility by private car	Tons/year

3. Block C. Transition measures to NZED

Block C comprises processes and technologies for transition to NZED.

The combined effect of these technologies should offset all CO_2 emissions produced by using fossil energy.

All measures of block C (C1-C8) have an impact on variables of Block B related to energy usage and CO_2 emissions.

Included are 8 types of measures applied at different spatial entities of the district:

C1. Housing: energy saving by building refurbishment
C2. Housing: energy saving by smart city solutions

C3. Public lighting: energy saving by smart city lighting
C4. Transport: Green mobility and energy saving

C5. Smart grid and storage
C6. Local RE: Photovoltaic panels
C7. Local RE: Heat pumps and geothermal heat pumps

C8. Nature-based solutions: Tree canopy and CO_2 offset

This is an initial portfolio of solutions to assess. In next versions of the model others can be added.

3. C1- Housing: energy saving by building refurbishment

Building energy retrofitting / refurbishment includes improving or replacing lighting, ventilation systems, replacing single-glazed with double glazing windows and doors, adding insulation on roof and external walls.

The EU service "Science for Environmental Policy" based on data from nine countries estimates that building refurbishment in existing housing could save 10% of energy for heating by 2020 and 20% by 2030.

Table 6: Expected savings potential under the EPBD for existing dwellings

	Country	Heat before (kWh/m)	Heat after (kWh/m2)	Saving %
Bulgaria	Houses	143	25	82,52
	Apartments	96	56	41,67
Czech Republic	Houses	190	68	64,21
	Apartments	194	134	30,93
Denmark	Houses	139	80	42,45
	Apartments	135	61	54,81
Germany	Houses	254	137	46,06
	Apartments	185	74	60,00
Finland	Houses	154	118	23,38
	Apartments	154	141	8,44
Latvia	Houses	273	202	26,01
	Apartments	217	145	33,18
The Netherlands	Houses	125	54	56,80
	Apartments	103	52	49,51
Portugal	Houses	114	45	60,53
	Apartments	117	46	60,68
U.K.	Houses	216	119	44,91
	Apartments	172	53	69,19

Source: Tuominen et al. (2012)

Energy heating saving = Energy reduction coefficient (x) * Energy consumption residential total (kWh) * Energy consumption residential-Heating (%)

$$E_{H\text{-}S} = 0.20 * E_{RT} * E_H$$

3. C2- Housing: energy saving by smart city solutions

A series of experiments and pilots in Amsterdam Smart City (Geuzenveld neighbourhood 500 homes, West Orange project 400 households, ITO Tower) for assessing the contribution of smart city solutions to energy saving shows energy saving between 4% and 18%

Residential projects for energy saving use smart meters and readable displays that enable users to be more aware of energy consumption, and even make it possible to see energy usage per appliance.

Energy lighting and appliances saving = Energy reduction coefficient (x) * Energy consumption residential total (kWh) * Energy consumption residential-Lighting & appliances (%)

ELA-S = 0.10 * ERT * ELA

3. C3- Public lighting: energy saving by smart city lighting

Improving ordinary city lighting with smart city solutions includes

1. Replacing lamps with LED lights that have lower energy consumption
2. Installing sensors for motion detection
3. Brightness adaptation to lights switch on when pedestrians are near, or vehicles pass and switch off in absence of movement.

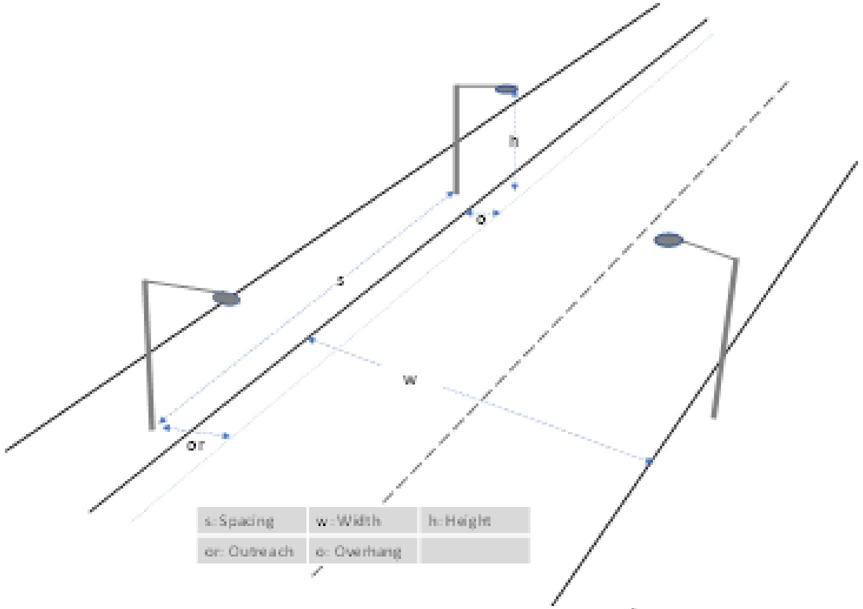


Figure 4: Street lighting layout
Adapted from: Subramani et al. 2019

- Nefedov et al. (2014, p.1718) estimate that "LED technology enables intelligent street lighting that is based on sensing individual vehicles and dimming streetlights accordingly. The potential energy savings are considerable, exceeding 50"
- Escolar et al. (2014) conducted simulations in the city of Leganés, a city with 50,000 lampposts : energy savings reach 55% relative to the nonadaptive application".

Energy saving - smart city lighting = Energy reduction coefficient (x) * Number of lighting poles on the grid * Street light lamp watt * Hours operation / year (kWh)

$$E_{SL\text{-}S} = 0.50 * P_L * L_W * H_Y$$

3. C4- Transport: Green mobility, energy, CO_2 emissions

Daily commuting	Current (based on statistics)	Impact on	NZED	Impact on	Units
Public transport	15%	kWh	15%	kWh	0.1 kWh/km
Private car	70%	CO_2	15%	CO_2	190 gr/km
Private car – electric vehicle	0%	kWh	50%	kWh	0.2 kWh/km
Micro-mobility - electric	5%	kWh	10%	kWh	0.02 kWh/km
Walking, cycling, non comm.	10%	-	10%	-	-

Energy for electric mobility = [Population * % workers * ev transport mode] * [average travel distance * number of travels per year] * energy consumption/km

$$E_{EV} = P * AP * z(ev) * Dtpc * Tpc * 0.2\ (0.05)\ \text{kWh/km (kWh)}$$

CO_2 emissions for mobility by private car = [Population * % workers * conventional car transport mode] * [average travel distance * number of travels per year] * CO_2 / km

$$C_{MPC} = P * AP * z(cc) * Dtpc * Tpc * 0.19\ \text{Kg/km (Kg)}$$

Travel distance per person per day by main travel mode for urban mobility on all days
(%)

	Belgium	Denmark	Germany	Greece	Croatia	Latvia	Netherlands	Austria	Poland	Portugal	Romania	Slovenia
By car as driver	54.4	53.8	58.0	44.6	59.6	54.8	49.6	50.6	48.2	57.3	30.4	65.2
By car as passenger	16.3	11.3	11.8	15.4	13.3	13.0	12.6	13.5	10.6	12.9	26.4	15.4
By taxi (as passenger)	0.1	0.3	0.2	1.3	0.4	0.5	0.0	1.1	0.0	0.4	2.5	0.2
By van/lorry/tractor/camper	0.0	8.1	2.2	0.8	2.3	0.0	0.0	0.0	0.0	0.0	0.0	1.1
By motorcycle and moped	0.8	0.9	0.6	7.0	0.1	0.3	2.0	1.0	0.6	1.3	0.1	0.2
By bus and coach	4.3	4.1	2.3	11.5	9.9	13.1	3.7	4.0	25.9	10.8	27.6	6.8
Urban rail	2.8	4.4	5.4	12.8	5.0	4.9	0.0	13.0	2.9	4.0	1.9	0.0
By train (total)	8.6	5.5	8.6	0.1	2.8	5.2	7.5	9.0	2.9	5.1	3.9	1.3
Aviation and waterways	0.0	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.5	0.0	0.0
Cycling	6.6	7.5	5.5	0.5	2.1	2.2	16.0	3.4	4.7	0.5	0.3	3.3
Walking	3.8	4.1	4.0	5.8	4.5	6.1	5.1	3.9	1.8	5.8	6.9	6.5

Source: Data from twelve Member States (nine pilot surveys and three national surveys on passenger mobility)

eurostat

Means of transportation	Number	Margin of error (±)	Percent	Margin of error (±)
Total	**156,941,346**	**161,399**	**100.0**	**0.1**
Car, truck, or van	133,054,328	173,377	84.8	0.1
Drove alone	119,153,349	145,368	75.9	0.1
Carpooled	13,900,979	82,351	8.9	0.1
Public transportation	7,778,444	42,450	5.0	0.1
Bus	3,601,403	34,897	2.3	0.1
Subway or elevated rail	2,935,633	29,091	1.9	0.1
Long-distance train or commuter rail	921,391	17,465	0.6	0.1
Light rail, streetcar, or trolley	242,776	8,667	0.2	0.1
Ferryboat	77,241	5,055	0.0	0.1
Taxicab	385,756	13,467	0.2	0.1
Motorcycle	221,923	7,785	0.1	0.1
Bicycle	805,722	19,868	0.5	0.1
Walked	4,153,050	43,355	2.6	0.1
Other means	1,571,323	27,465	1.0	0.1
Worked from home	8,970,800	53,611	5.7	0.1

Means of transportation to work in the US, 2019
US Census Bureau, 2019 American Community Survey, mobility of workers 16 years and over
Source: Burrows, M., Burd, C., and McKenzie, B. (2021)

3. C5-Smart grid and energy storage

The smart grid is the backbone of the Net Zero Energy District. A smart grid is "a class of technology using computer-based remote control and automation. These systems are made possible by two-way communication technology and computer processing that has been used for decades in other industries" (U.S. Department of Energy)

Smart grids support three functions

- ***integration of distributed energy resources*** located in the district,
- ***energy storage*** to secure uninterrupted supply of energy to users, and
- ***real-time monitoring of energy flows***, enabling awareness, optimisation, and service provision to producers and consumers.

In transition measures to NZED, the smart grid is a condition for the integration of the measures proposed (C1-C8) balancing RE supply and demand. The added value in terms of energy efficiency is included in measures C6 and C7 of local renewable energy production.

3. C6- Local renewable energy by photovoltaic panels

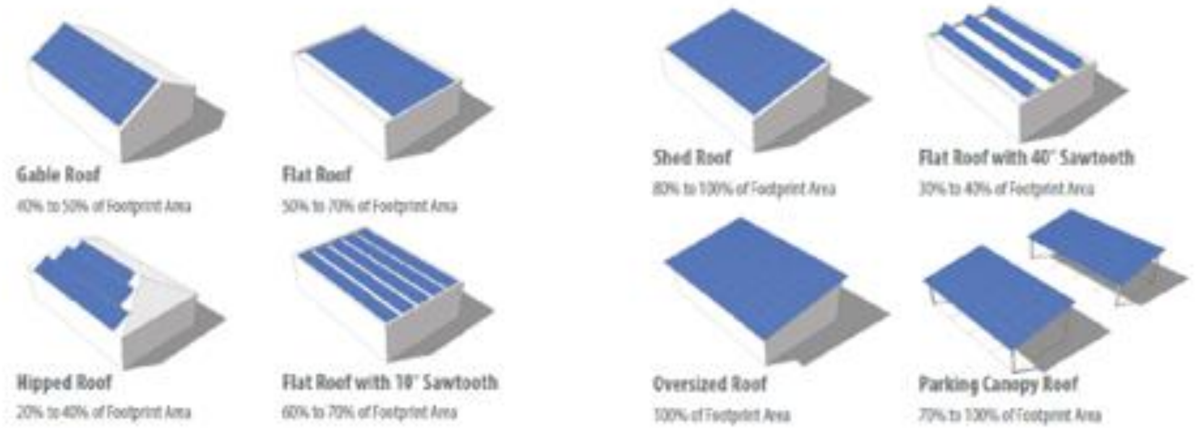


Figure 5: Placing photovoltaic panels on building roof
Source: Polly et al., 2020

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)	Value ($)
January	2.80	1,531,463	N/A
February	3.47	1,725,309	N/A
March	4.56	2,485,046	N/A
April	5.50	2,829,351	N/A
May	6.30	3,299,492	N/A
June	7.43	3,691,009	N/A
July	7.59	3,857,202	N/A
August	7.05	3,569,668	N/A
September	6.23	3,095,889	N/A
October	4.30	2,276,061	N/A
November	2.73	1,422,473	N/A
December	2.45	1,336,004	N/A
Annual	5.03	31,118,967	0

PV panels surface: 0.70*Housing area*BRC + 0.10*Housing area + 0.10 Road and parking area

PVs = 0.70 * Ah + 0.1 * Ah + 0.1 Ar (sm)

DC system size = 0.217 * PV panels surface (kW)

Energy from PV panels = DC system size *solar irradiance

ERE = f(DC system size) (kWh/year)

Luxembourg's first floating PV plant is now operational

NOVEMBER 22, 2021 EMILIANO BELLINI

MARKETS UTILITY SCALE PV LUXEMBOURG

The facility was deployed with 25,000 solar modules on a former cooling pond owned by Arcelormittal.

Waterproof Solar Carport | Processional supplier for the Roof Mounting, Ground Mounting, Solar Farm, Solar Carport

3. C7-Air source heat pumps and geothermal heat pumps

This type of renewable energy can be used to reduce energy consumption for space heating (E_H) and domestic water heating (E_{DWH}).

Simulations and experimental studies assess energy saving of heat pump-based heating systems. Zanetti et al. [2000] reviewing papers that compared different solutions of photovoltaic assisted by air-source heat pumps show a potential of energy saving between 20-35%. Geothermal heat pumps contribute to CO_2 emissions less than half compared to conventional oil boiler systems. The Energy Saver, U.S. Department of Energy, assess that heat pump can reduce your electricity use for heating by approximately 50%.

Energy saving heating = Energy reduction coefficient (x) * Energy consumption residential total (kWh) * Energy consumption residential-Lighting & appliances (%)

$$E_{H-S} = 0.35 * E_{RT} * E_H$$

Energy saving domestic water heating= Energy reduction coefficient (x) * Energy consumption residential total (kWh) * Energy consumption residential- domestic water heating (%)

$$E_{DWH-S} = 0.35 * E_{RT} * E_{DWH}$$

3. C8-Nature based solutions

The concept of ‘Nature-based solutions’ (NbS) was introduced by the World Bank to underline the positive role of biodiversity in climate. Examples of NbS include trees in urban parks and forests, street trees, reduction of urban heat islands, conservation of natural habitat space in floodplains, architectural solutions for buildings, green roofs, wall insulation, and others.

We use tree canopy to remove CO_2. Trees can be planted in three areas:

- Public gardens and city forests can contain 500 trees per hectare. We propose 60% of green spaces to be covered by trees.
- Roads with trees at both sides with an average distance of 5 m between them, can contain 400 trees / km.
- Private gardens and yards. We propose 25% of their surface to be covered by trees.

The CO_2 absorption capacity of trees is estimate at 24 kg / tree / year (increases with the age of trees)

CO_2 absorption = Number of trees * CO_2 absorption / tree

$$CO_2\text{-a} = [f(Ag)+f(Rlg)+f(Ah)] * 24 \text{ kg } CO_2 \text{ /tree (Kg)}$$

Ag=green area, Rlg=road length, Ah=housing area

Block D. Energy & CO2 balance

Energy balance	Carbon balance
[Total energy consumption in housing, street lighting, mobility by public transport and electromobility] - [energy saving from smart system measures to NZED] < [renewable energy generated by PV panels]	[CO2 emissions in mobility by private vehicles using fossil fuels] < [CO2 removed by nature-based solutions]

The overall model we use for this analysis can be described by using the following equations:

$$\sum E - \sum E_S < E_{RE} \qquad (1)$$

Where $\sum E$ refers to the total energy consumption in housing (E_R), street lighting (E_{SL}), mobility (E_M) including private cars (E_{MPC}), public transport (E_{MPT}) and electromobility (E_{MEV}); $\sum E_S$ refers to energy savings from heating (E_{H-S}), lighting and appliances (E_{LA-S}), smart city lighting (E_{SL-S}) and electric mobility (E_{EV}); and E_{RE} refers to the energy generated by PV panels.

And

$$C_{MPC} < CO2_a \qquad (2)$$

Where C_{MPC} refers to the CO2 emissions from mobility by private car; and $CO2_a$ to the capacity of CO2 absorption by tree canopy in a district.

4. Simulations: Baseline scenario, D gross = 100 in/ha (D net = 200 in/ha)

Block A

Code	Name	Measurement unit	Value
	Demographics		
P	Population	Physical persons	5,000
AP	Active population as % of total	Working person	40
H	Number of households	Household	1,500
D	Density	Persons/Hectare	100
	Land use		
At	Total area of the district	Hectare	50
Ah	Housing area, 50% to total	Hectare	25
As	Social care, education, culture, sports area, 0% of total	Hectare	0
Ar	Local retail and services area, 0% of total	Hectare	0
Ar	Road and parking area, 20 % of total	Hectare	10
Ag	Green, gardens, urban forests area, 30% of total	Hectare	15
	City grid and public ligthing		
Bb	Number of building blocks on the grid	Building block	169
Pl	Number of lighting poles on the grid	Pole	676
Rlg	Road length of the district grid	Kilometre	12
	Building code		
BCR	Building Coverage Ratio	Percentage	40
FAR	Floor-Area Ratio	Number	0.80
Hfpc	Housing floor per capita	Square meter	40
Bnf	Number of building floors	Floor	2
	Mobility		
Tpc	Number of commuting travels per worker per year	Travel	500
Dtpc	Average distance per commuting travel	Kilometre	10
Pmpc	People using private car in commuting-% of total	Percentage	70
Pmpt	People using public transport in commuting- % of total	Percentage	15
Pmgr	People using bicycle, walk, or work from home-% of total	Percentage	15

Grid	Plot (in meters)		Area	FAR	Foor area	SM/person	Persons
Plot dimensions	50	50	2500	0.8	2000	40	50
Residential area			250,000				5,000
B. blocks housing			100				
Green area			150,000				
B. blocks green area			60				
Σbuildingbloks			160				

Grid 50*50	B. blocks	Poles/Bb	Poles
Total number	**169**	**4**	**676**

Roads (in meters)		
Length per row	858	
Number of rows	14	
Total length	12,012	
Road width	8	
Road area	96,096	< 10,000

4. Simulations: cities in southern, central, northern Europe

BLOCK A

Code	Name	Measurement unit	Value
	Demographics		
P	Population	Physical person	5,000
AP	Active population as % of total	Working person	40
H	Number of households	Household	1,500
D	Density	Persons/Hectare	100
	Land use		
At	Total area of the district	Hectare	50
Ah	Housing area, 50% to total	Hectare	25
As	Social care, education, culture, sports area, 0% of total	Hectare	0
Ar	Local retail and service		
Ar	Road and parking area		
Ag	Green, gardens, urban		
	City grid and public lig		
Bb	Number of building blo		
Pl	Number of lighting pol		
Rlg	Road length of the dist		
	Building code		
BCR	Building Coverage Rati		
FAR	Floor-Area Ratio		
Hfpc	Housing floor per capi		
Bnf	Number of building flo		

BLOCK B

Residential energy consumption

Code	Name	Measurement unit	Value	Breakdown	Unit
P	Population	Person	5,000		
EPC	Energy consumption total per capita	kWh/year	30384		
ERPC	Energy consumption residential per capita, % of total	Percentage	26.30%		
ERT	Energy consumption residential, total	kWh/year	39,954,960		
EH	Energy consumption residential-Heating	Percent of total	63.60%	25,411,355	kWh/year
ELA	Energy consumption residential-Lighting & appliances	Percent of total	14.10%	5,633,649	kWh/year
EDWH	Energy consumption residential-Domestic water heating	Percent of total	14.80%	5,913,334	kWh/year
EC	Energy consumption residential-Cooking	Percent of total	6.10%	2,437,253	kWh/year
ECL	Energy consumption residential-Cooling	Percent of total	0.40%	159,820	kWh/year

ption in households by type of end-use

676
0.25
6.69
,841

BLOCK C

C1	**Housing: energy saving by building refurbishment**	**Energy reduction coefficient (x)**	**Energy consumption residential total (kWh)**	**Energy consumption residential-Heating (%)**			**Energy saving**		
	Energy saving for heating (EH-S)	0.2	39,954,960	63.60%			5,082,271		kWh
C2	**Housing: energy saving by smart city solutions**	**Energy reduction coefficient (x)**	**Energy consumption residential total (kWh)**	**Energy consumption residential-Lighting & appliances (%)**			**Energy saving**		
	Energy saving for lighting and appliances (ELA-S)	0.1	39,954,960	14.10%			563,365		kWh
C3	**Public lighting: energy saving by smart city lighting**	**Energy reduction coefficient (x)**	**Energy consumption street lighting (kWh)**				**Energy saving**		
		0.5	776,841				388,420		kWh

C4	**Transport: Green mobility, energy and CO2 emission**	**Population**	**% workers**	**% mode (z)**	**Average travel dist**	**NumTravels**	**kWh/km or CO2/km**	**Value**	**Units**
	Mobility by public transport	5,000	40%	15%	10	500	0.1	150,000	kWh
	Mobility by electric vehicles	5,000	40%	50%	10	500	0.2	1,000,000	kWh
	Mobilily e-micromobility	5,000	40%	10%	10	500	0.05	50,000	kWh
	Total e-mobility							1,200,000	
	CO2 emissions in mobility by private car	5,000	40%	15%	10	500	0.19	285,000	Kg

C5	**C5. Smart grid and energy storage**
	Saving and RE support included in other measures

		PV area: buildings +	PV coverage	PV surface	Power per sm	DC system	Yearly production		Unit

District | **Athens-100** | Frankfurt-100 | Helsinki-100 | Athens-120 | Frankfurt-56 | Helsinki-43 | Frankf-PCE2 | Hels-PCE2

4. Simulations: Feasibility of NZEDs – H1

Energy	**Athens-100**			**Frankfurt-100**			**Helsinki-100**		
Energy consumption									
Residential	39,954,960			57,469,445			72,480,170		
Public lighting	776,841			732,529			710,052		
Mobility	1,200,000			1,200,000			1,200,000		
Energy saving									
C1: Building refurbishment		5,082,271			7,310,113			9,219,478	
C2: Smart home solutions		563,365			810,319			1,021,970	
C3: Smart city ligthing		388,420			366,264			355,026	
C7: Heat pumps		10,963,641			15,769,616			19,888,559	
Renewable energy generation									
C6: PV panels			31,118,964			20,115,406			19,342,450
Total energy	41,931,801	16,997,697	31,118,964	59,401,974	24,256,313	20,115,406	74,390,222	30,485,033	19,342,450
Energy balance in NZED (kWh)	**6,184,861**			**-15,030,255**			**-24,562,739**		
CO2									
C4: CO2 emissions	285,000			285,000			285,000		
C8: CO2 capture		298,200			298,200			298,200	
CO2 balance in NZED (Kg)	**13,200**			**13,200**			**13,200**		

Energy usage		24,934,103			35,145,661			43,905,189	
RE surplus or gap		36.39%			-42.77%			-55.94%	
Energy saving		40.54%			40.83%			40.98%	
RE/energy needs		124.80%			57.23%			44.06%	

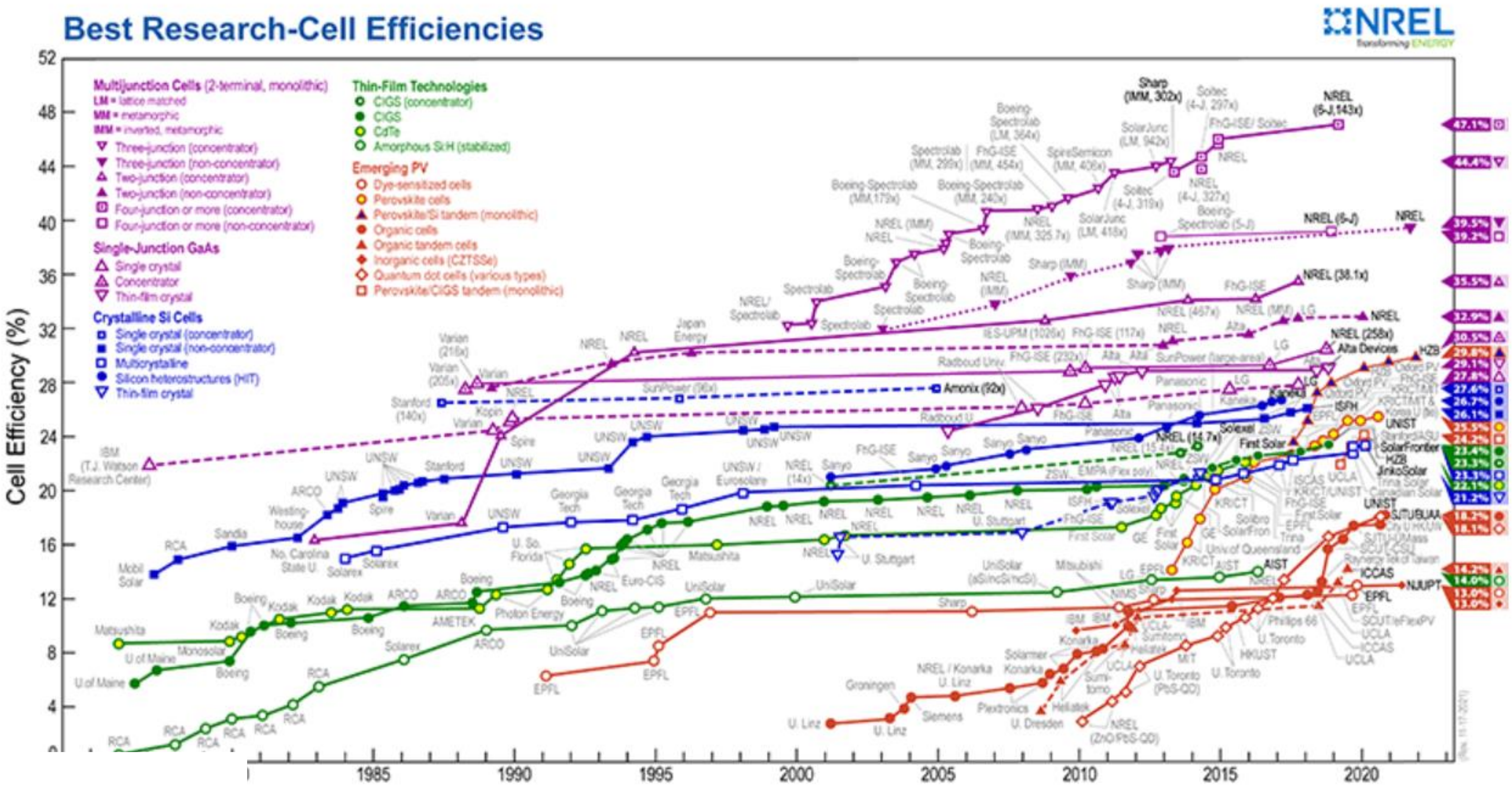
The outcomes of the baseline scenario show that the transition to NZED is feasible in Athens, but not feasible in Frankfurt and Helsinki. The same outcome are for cities in southern Europe (Madrid, Rome), central Europe (Lyon, Munich, Vienna) and northern Europe (Stockholm)

4. Simulations: Critical thresholds for carbon neutrality – H2

Energy	Athens-100			Frankfurt-56			Helsinki-43		
Energy consumption									
Residential	47945952			32,182,889			31,166,473		
Public lighting	776840.61			732,529			710,052		
Mobility	1440000			672,000			516,000		
Energy saving									
C1: Building refurbishment		6098725.1			4,093,664			3,964,375	
C2: Smart home solutions		676037.92			453,779			439,447	
C3: Smart city ligthing		388420.31			366,264			355,026	
C7: Heat pumps		13,156,369			8,830,985			8,552,080	
Renewable energy generation									
C6: PV panels			31,118,964			20,115,406			19,342,450
Total energy	50,162,793	20,319,553	31,118,964	33,587,418	13,744,691	20,115,406	32,392,525	13,310,929	19,342,450
Energy balance in NZED (kWh)	**1,275,724**			**272,679**			**260,854**		
CO2									
C4: CO2 emissions	342,000			159,600			122,550		
C8: CO2 capture		298,200			298,200			298,200	
CO2 balance in NZED (Kg)	**-43,800**			**138,600**			**175,650**		

Critical thresholds are:

- ***Density***: the baseline scenario becomes feasible with lower densities in Frankfurt (56) and Helsinki (43)
- ***Electric mobility***: commuting with a private car at the level **of 15%** of the active population
- ***Solar panel power conversion efficiency*** (PCE): Doubling PCE, the baseline scenario becomes feasible throughout Europe (should be expected within the decade, research is already there)



New World Record: Almost 30% Efficiency for Next-Generation Tandem Solar Cells

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By HELMHOLTZ CENTRE FOR MATERIALS AND ENERGY, HZB NOVEMBER 28, 2021

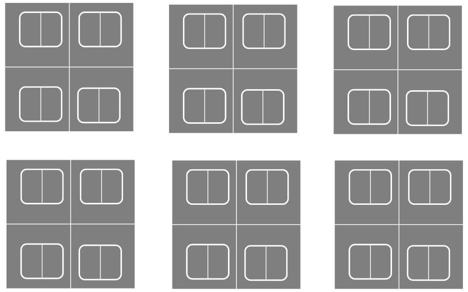
https://www.nrel.gov/pv/cell-efficiency.html

4. Simulations: Rejection of the compact city concept – H3

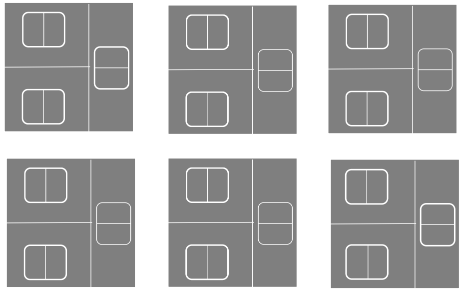
Following LEED-ND (v4. 2018) in compact city districts **residential density**, in districts located within walking distances to transit service, **should be 12 or more dwelling units per acre** (or 30 DU per hectare) of buildable land available for residential uses.

The outcome of the NZED model shows that a net density of 200 inhabitants per hectare (100 gross density) is the **upper limit for a self-sufficient NZED in southern Europe**, a density which is limited further at the level of 100 net density in central and northern Europe.

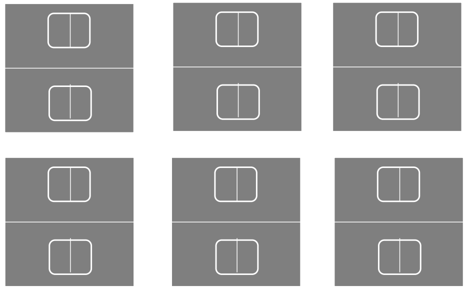
These densities correspond to floor space between 8,000 and 4,00 square meters per hectare or **32 – 16 dwelling units per hectare**, which do not comply with a compact city form.



Inhabitants/building block: (2500 *0.8) / 40 = 50
Net density: 50/2500 = 200 in/ha or 32 DU/Ha



Inhabitants/building block: (2500 *0.6) / 40 = 37.5
Net density: 37.5/2500 = 150 in/ha or 24 DU/Ha



Inhabitants/building block: (2500 *0.4) / 40 = 25
Net density: 25/2500 = 100 in/ha or 16 DU/Ha

5. Conclusion. Connected intelligence and transition to NZEDs

The model we developed shows that currently self-sufficient NZEDs based on PV panels are feasible in southern Europe, but not in central and northern Europe.

- Technologies that improve the power conversion efficiency at the level of 40-45% will open the road for transition to NZEDs to any region.
- For a long period of time, when more than 15% of the district's residents continue to use fossil fuel vehicles in commuting, the district will function as a "near" rather than a "net" zero energy district without balancing CO_2 emissions.
- The transition to NZED is a project that will take a decade or more to complete.

We studied 8 measures of transition related to behaviours and intelligence of three types of agents. **Higher is the impact of measures related to human behaviour.**

Human behaviour, decisions should include

- Investing in renewable energy
- Using of electric vehicles and e-micro-mobility
- Connecting homes to the smart grid
- Sharing energy within the district

Community behaviour, decisions should include

- Setting energy communities
- Control of population density
- Planning rules for solar panel installation
- Development of a smart grid in the district
- Sharing energy under barter exchanges
- Upgrade of public transport to electromobility

Machine capabilities should include

- Smart city systems, smart grid, and smart meter
- Platforms for local energy transactions
- Making available performance data and analytics
- Using algorithms for automation in energy-saving
- Optimisation through energy sharing over the local smart grid

Thank you!