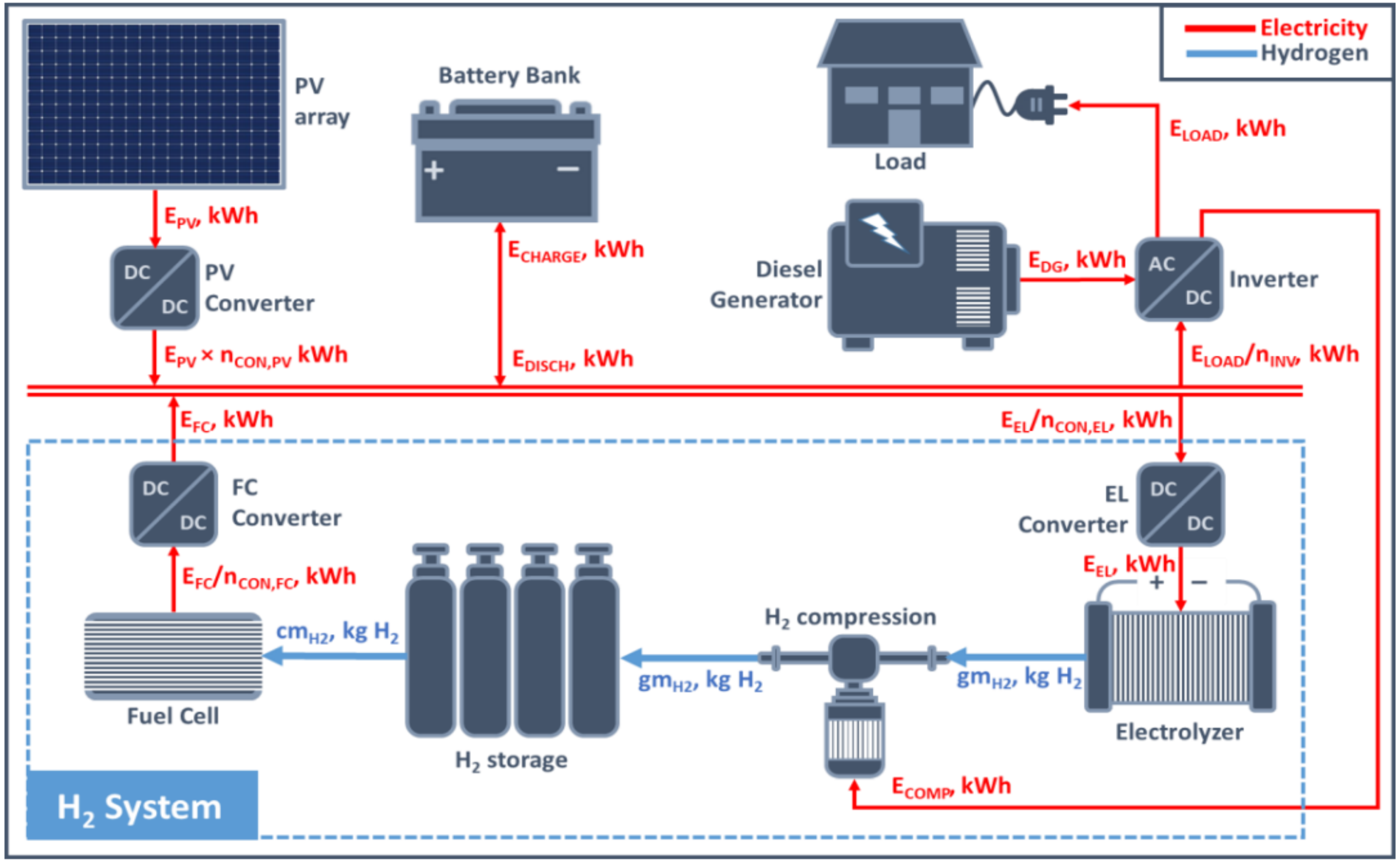
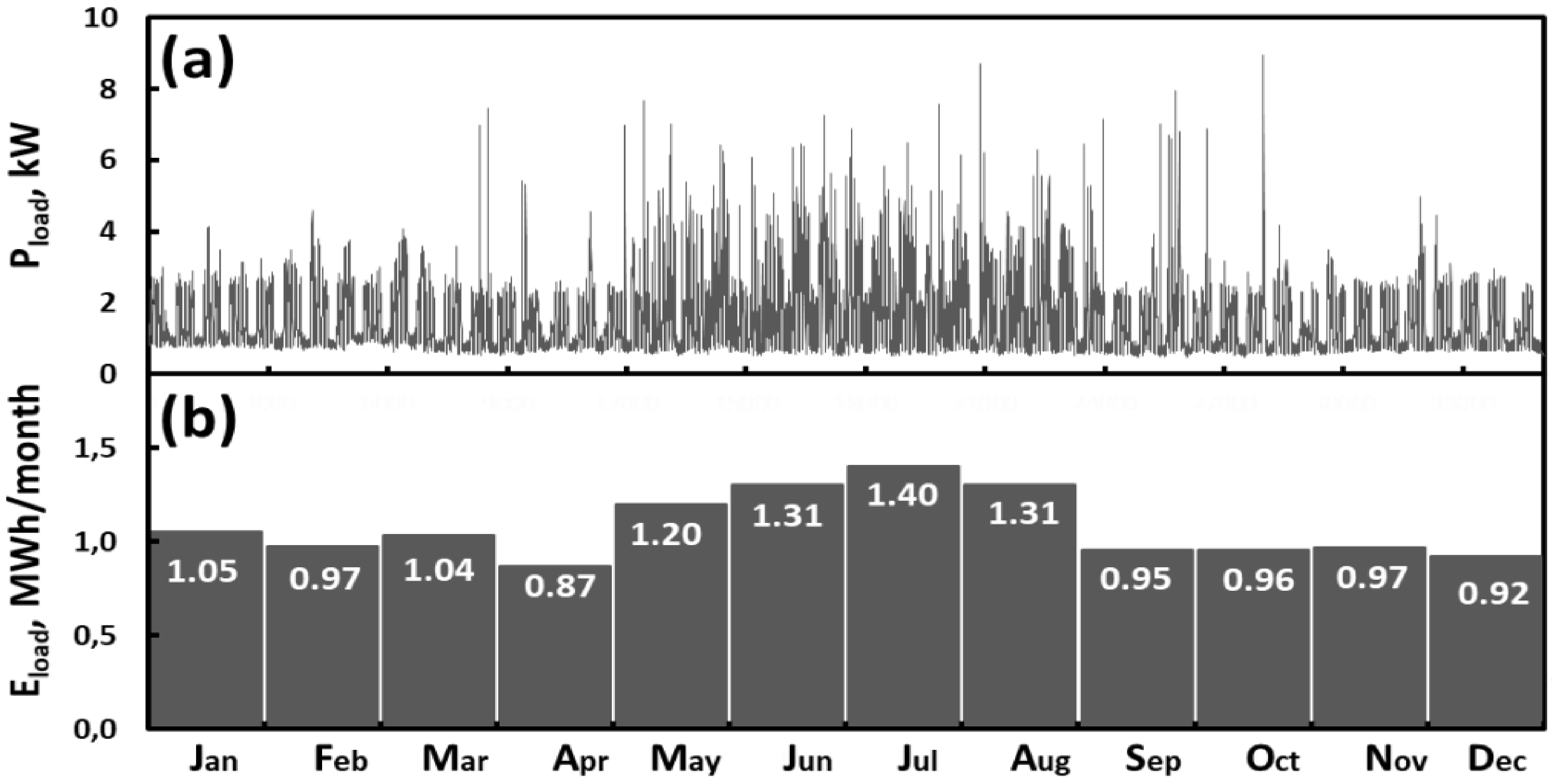
Power Management Strategy for the effective sizing of a PV Hybrid Renewable Energy System with battery and H_2 storage.

Block diagram of the PV Hybrid Renewable Energy System.

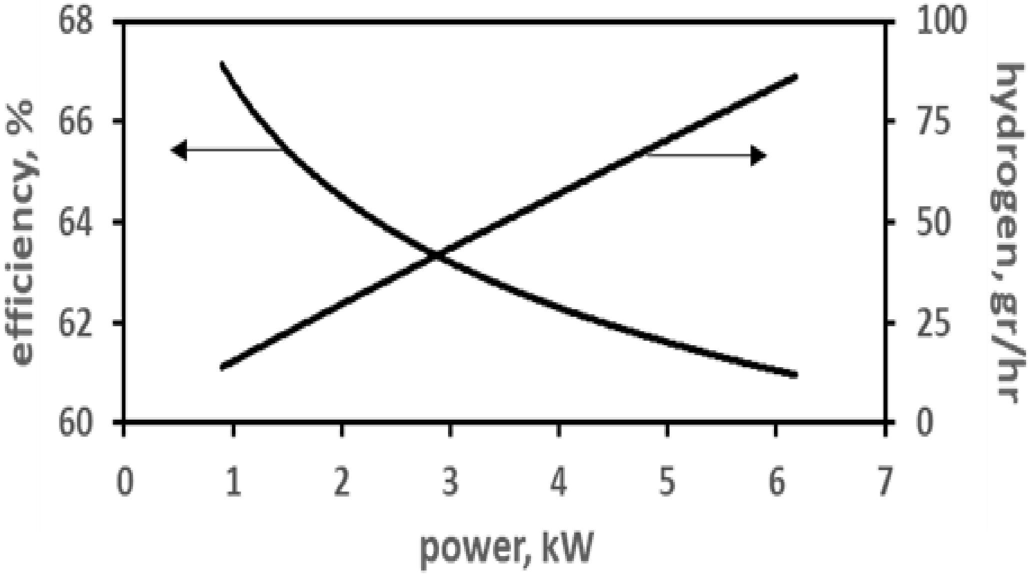


Annual load profile



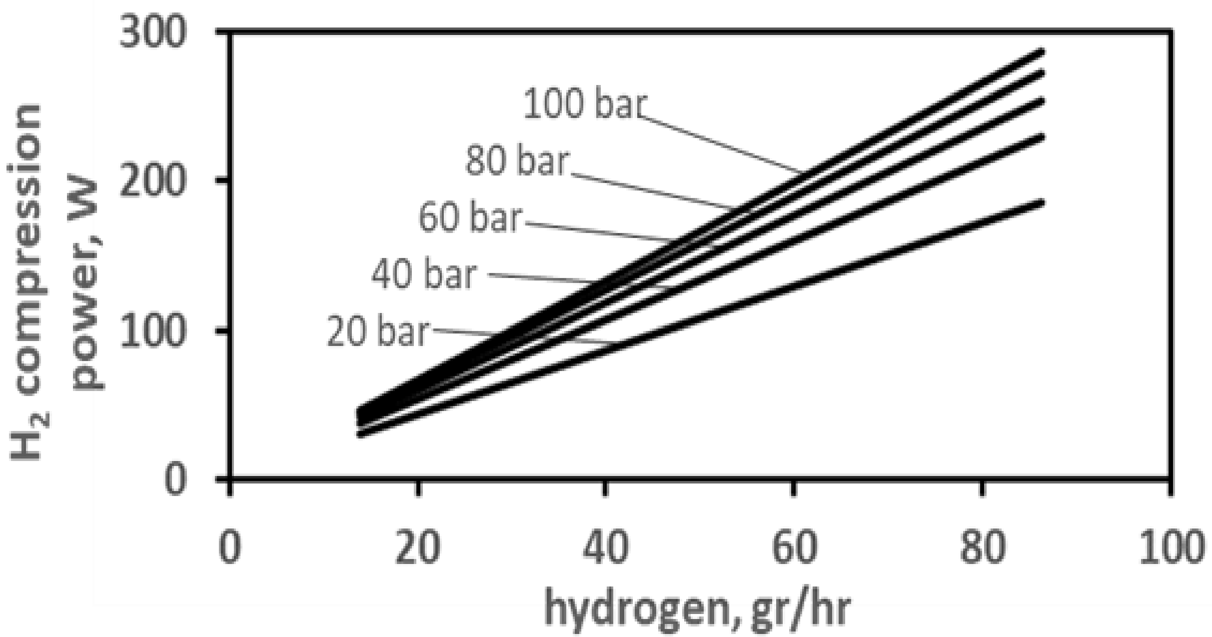
Dependence of the electrolyzer's efficiency and H_2 generation on power consumption.

$$EL_{eff} = 66.8 \times P_{el}^{-0,05}$$



$$GM_{H2} = 0.0153 \times P_{el}^{0.95}$$

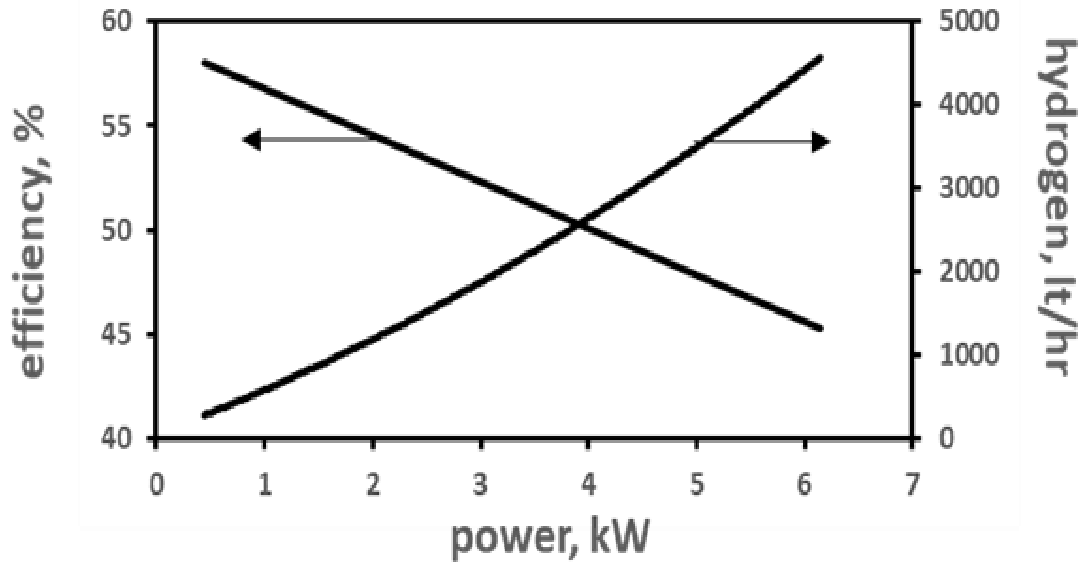
Power consumption for H_2 compression



$$PW_{comp} = (976.62 \times P_{cyl}^{0,27}) \times GM_{H2}$$

Dependence of the fuel cell's efficiency and H_2 consumption on power generation

$FC_{eff} = 59.0 – 2.23*P_{FC}$

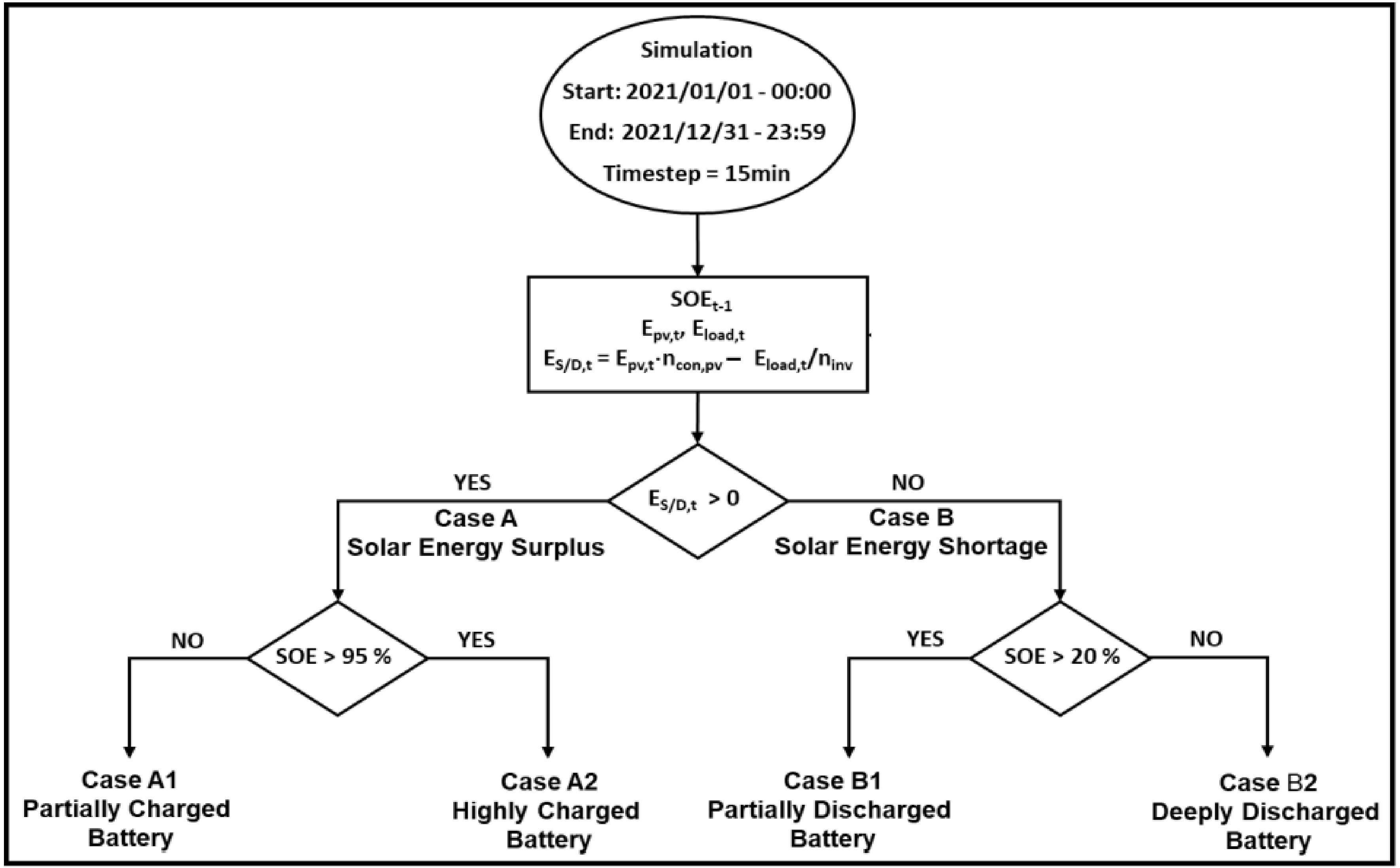


$CM_{H2} = 2.78* P_{FC}^2 + 33.17*P_{FC} + 4.24$

Design characteristics of the hydrogen system elements

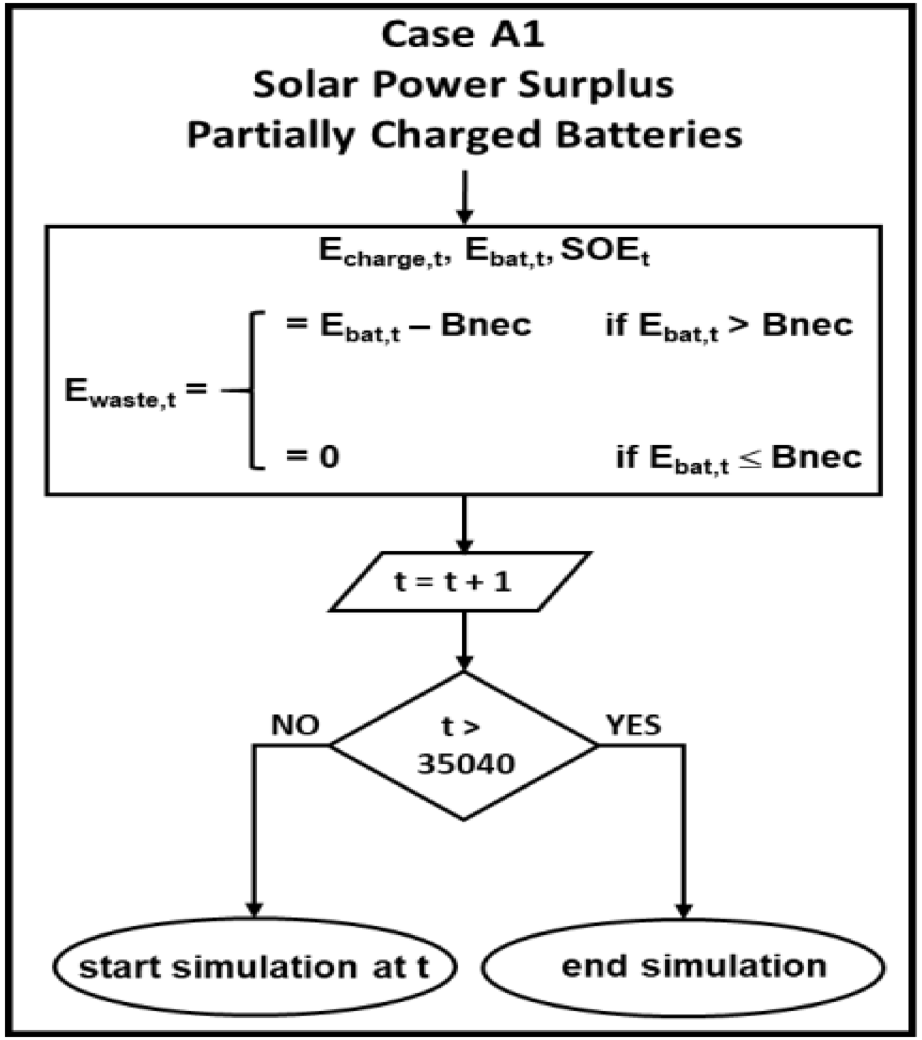
Alkaline Electrolyzer		**PEM Fuel Cell**	
Power, kW	0.90 – 6.18	Power, kW	0.44 – 6.15
Voltage, V	50 – 56	Voltage, V	67 – 88
Current, A	18 – 111	Current, A	5 – 92
Efficiency, %	60 – 68	Efficiency, %	44 – 59
H_2 generation, gr/hr	13.9 – 86.2	H_2 consumption, gr/hr	17.3 – 318.1
Hydrogen Compression		**Hydrogen Storage**	
Pmax, bar	100	Pmax, bar	100
Power, kW	<0,29	Maximum storage capacity, kgH_2	30.5 – 53.3
Compression rate, lt(STP)/hr	<1,256	Number of 50 lt cylinders	80 – 140

Flowchart of the Energy Management Strategy



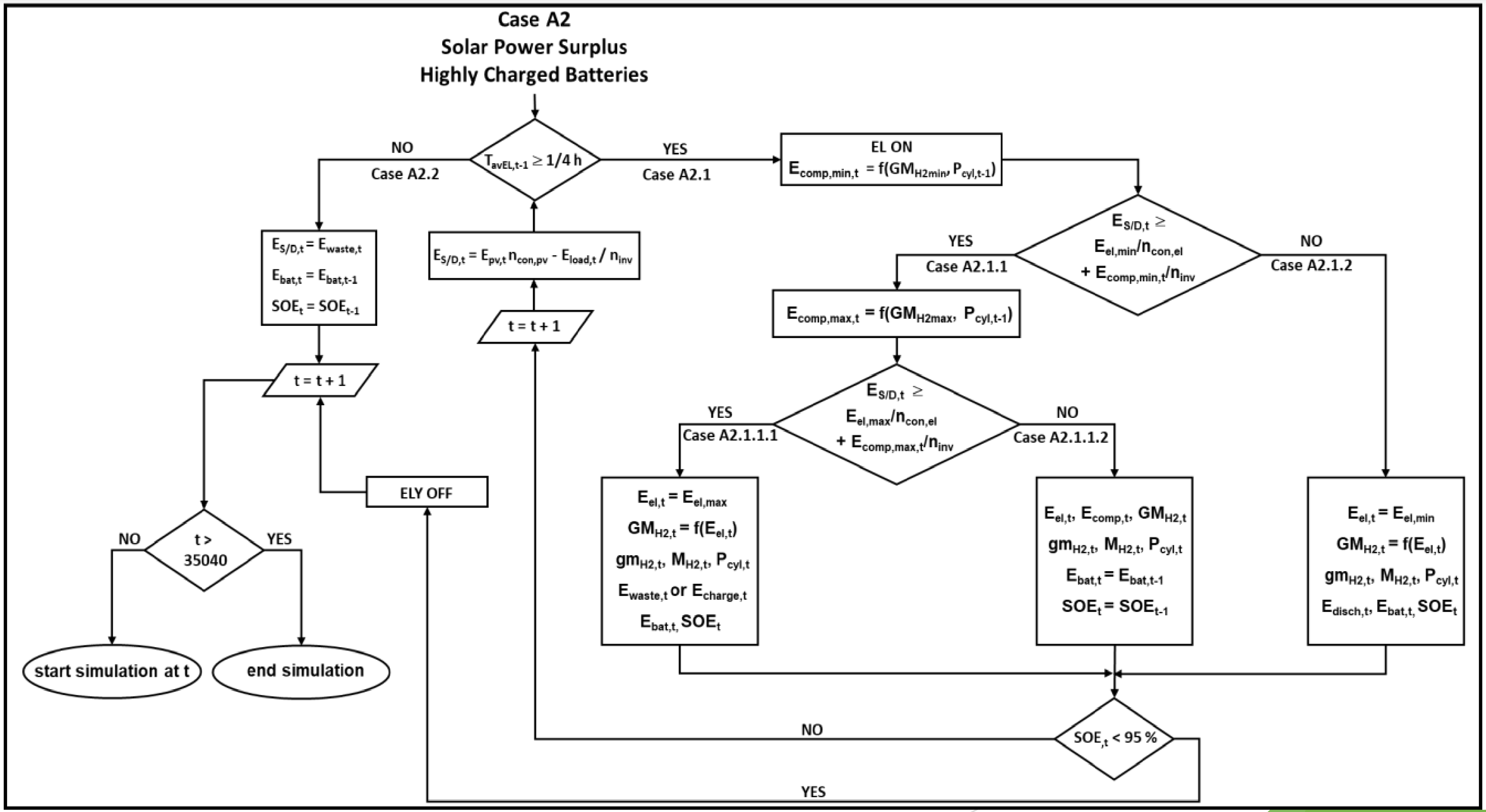
Case A1: Solar Energy Surplus – Partially Charged Battery

$E_{S/D,t} > 0$ *and* $SOE < 95\%$



Case A2: Solar Energy Surplus – Highly Charged Battery

$E_{S/D,t} > 0$ and SOE > 95%



Case A2: Solar Energy Surplus – Highly Charged Battery

H_2 storage availability variable: $$T_{avEL,t-1} = \frac{M_{H2,max} - M_{H2,t-1}}{GM_{H2,max}}$$

$M_{H2,max}$ *is the maximum mass of H_2 that can be stored in kg,*

$M_{H2,t-1}$ *is the mass of stored hydrogen, at time "t-1", in kg, and*

$GM_{H2,max}$ *is the maximum H_2 production rate, in kg/hr.* $GM_{H2} = 0.0153 \times P_{el}^{0.95}$

Case A2: Solar Energy Surplus – Highly Charged Battery

Case A2.1.1.1 $E_{S/D,t} \geq E_{el,max}/n_{con,EL} + E_{comp,max,t}/n_{inv}$

Produced H_2 (in kg) $gm_{H2,t} = GM_{H2,t} \cdot \Delta t$

Total mass of stored H_2 (in kg) $M_{H2,t} = M_{H2,t-1} + gm_{H2,t}$

Residual energy $E_{res,t} = E_{pv,t} \cdot n_{con,pv} - (E_{load,t} + E_{comp,t})/n_{inv} - E_{el,max}/n_{con,EL}$

- *If* $E_{res} \leq B_{nec} - E_{bat,t-1}$ *then* $E_{charge,t} = E_{res,t}$
- *If* $E_{res} > B_{nec} - E_{bat,t-1}$ *then* $E_{charge,t} = B_{nec} - E_{bat,t-1}$ *and* $E_{waste,t} = E_{res,t} - (B_{nec} - E_{bat,t-1})$

Case A2.1.1.2 $E_{el,min}/n_{con,EL} + E_{comp,min,t}/n_{inv} < E_{S/D,t} < E_{el,max}/n_{con,EL} + E_{comp,max,t}/n_{inv}$

$$E_{el,t} = \left(E_{S/D,t} - \frac{E_{comp,t}}{n_{inv}}\right) \times n_{con,EL}$$

$$GM_{H2,t} = 0.0153 \times E_{el,t}^{0.95}$$

$$E_{comp,t} = 976.62 \times P_{cyl,t-1}^{0.27} \times GM_{H2,t}$$

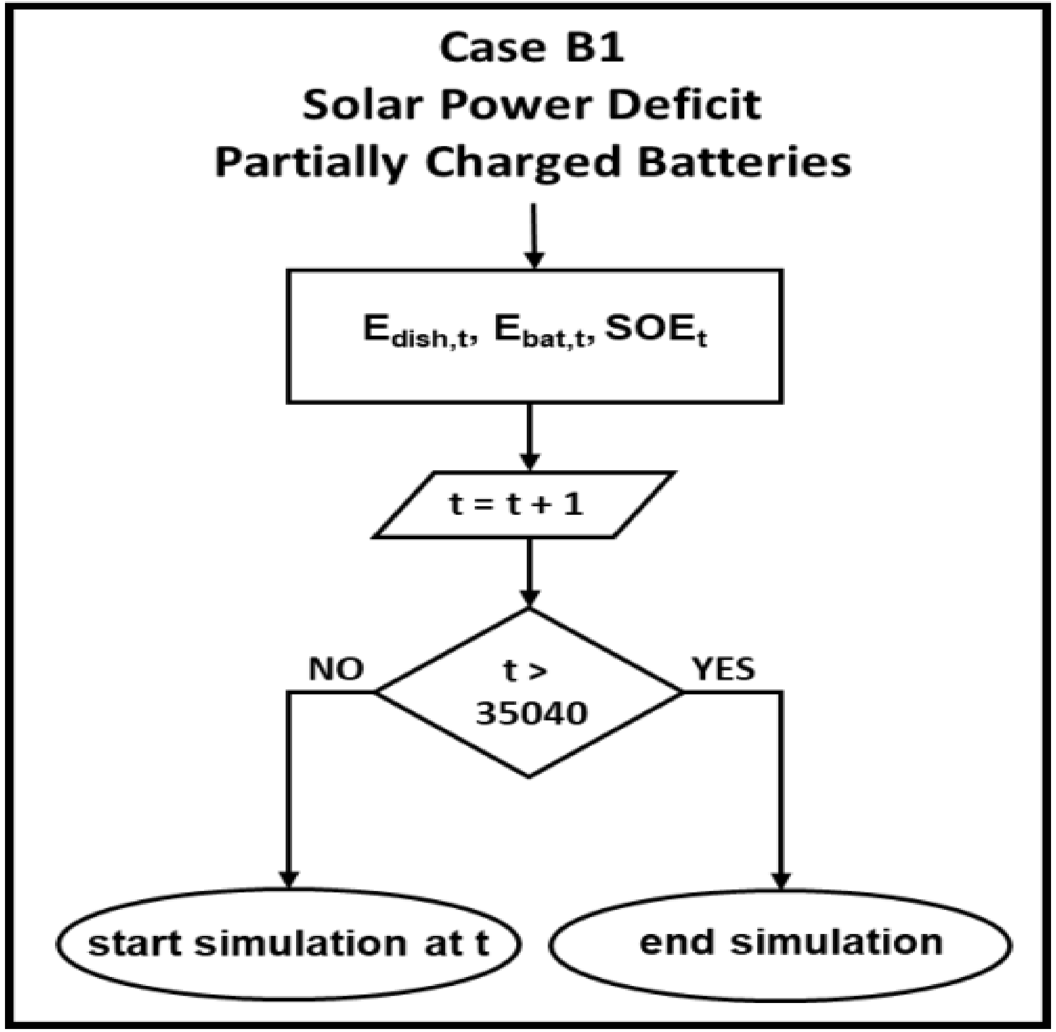
→ $E_{el,t}$, $GM_{H2,t}$, $E_{comp,t}$

Case A2.1.2 $E_{S/D,t} < E_{el,min}/n_{con,EL} + E_{comp,min,t}/n_{inv}$

$$E_{disch,t} = \frac{E_{el,min}}{n_{con,EL}} + \frac{E_{comp,min,t}}{n_{inv}} - E_{S/D,t}$$

Case B1: Solar energy deficit and partially discharged batteries.

$E_{S/D,t} < 0$ *and* $SOE > 20\%$

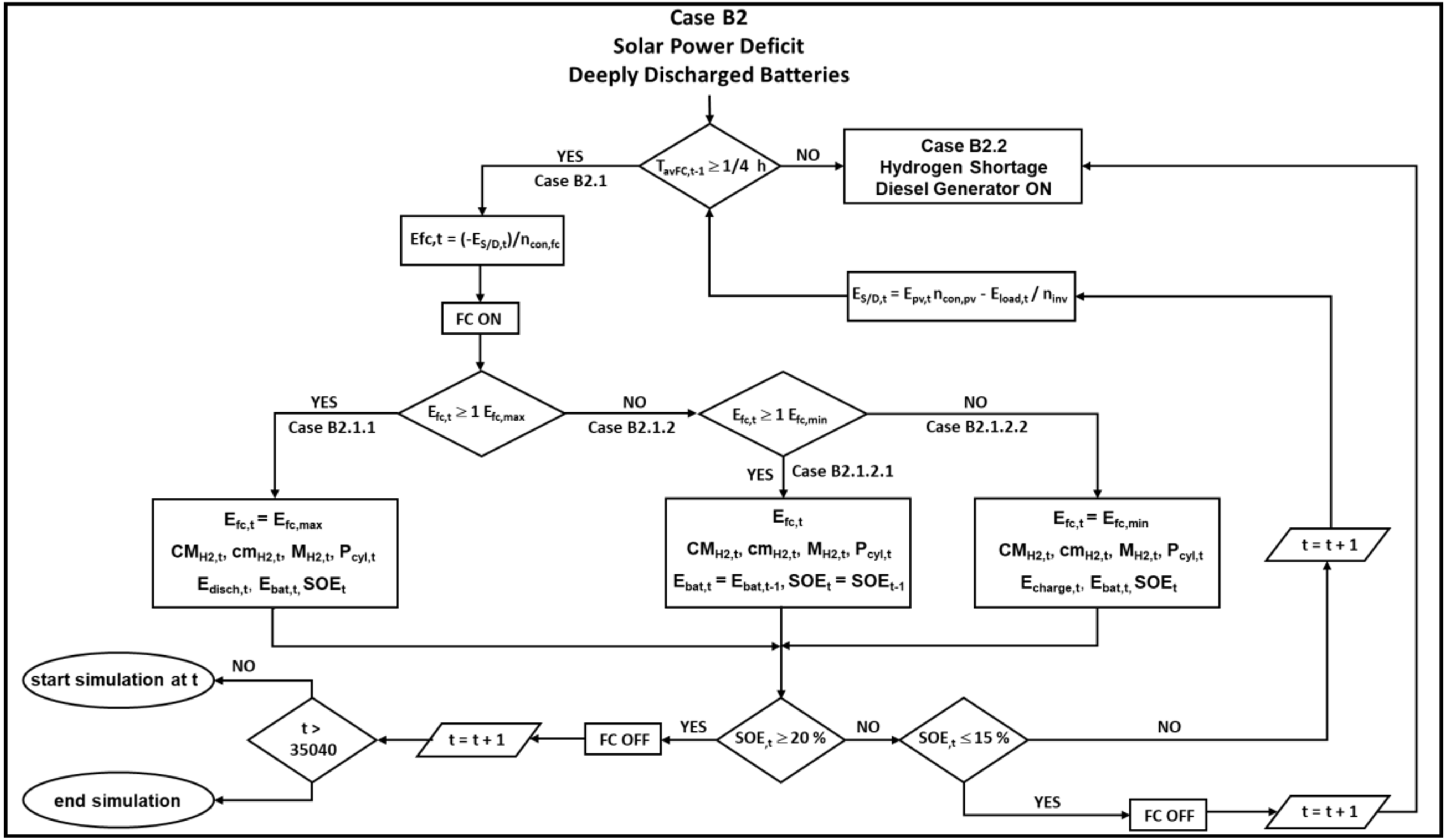


$$E_{disch,t} = \frac{E_{load,t}}{n_{inv}} - E_{PV,t} n_{con,pv}$$

$$E_{bat,t} = E_{bat,t-1} - E_{disch,t}$$

Case B2: Solar energy deficit and deeply discharged batteries.

$E_{S/D,t} < 0$ *and* $SOE < 20\%$



Case B2: Solar energy deficit and deeply discharged batteries.

Required time of FC to operate at its maximum power output

$$T_{avFC,t-1} = \frac{M_{H2,t-1} - M_{H2,min}}{CM_{H2,max}}$$

$M_{H2,t-1}$ and $M_{H2,min}$ are the stored H_2 mass (kg) at "t-1" and the defined minimum stored H_2 mass (kg), respectively.

$CM_{H2,max}$ the maximum H_2 consumption, kg/hr $CM_{H2} = 2.78 * P_{FC}^2 + 33.17 * P_{FC} + 4.24$

Case B2: Solar energy deficit and deeply discharged batteries.

Case B2.1: Fuel Cell operation (PV energy shortage, SOE ≤20 % B_{NEC}, H_2 availability)

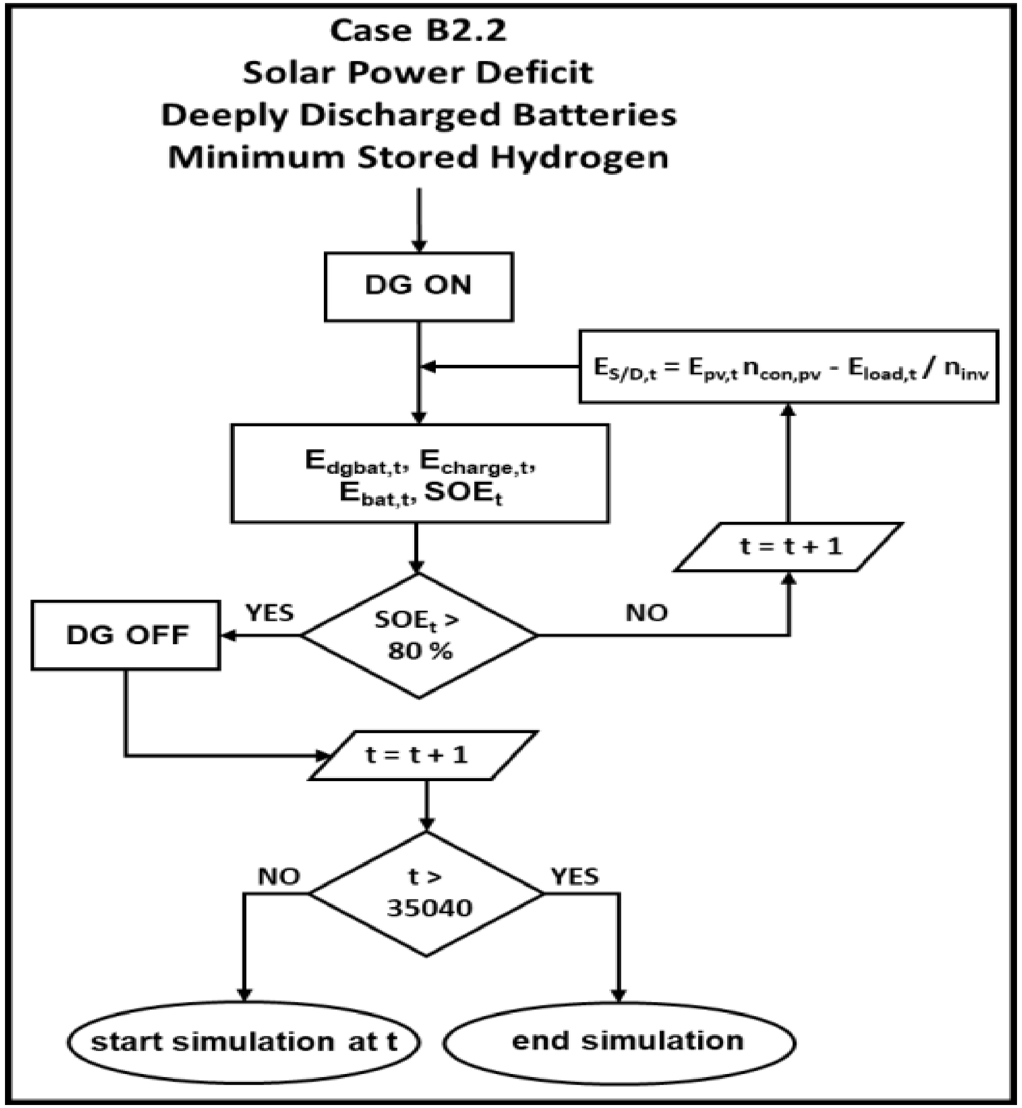
$$E_{fc,t} = \frac{-E_{S/D,t}}{n_{con,fc}} = \left(\frac{E_{load,t}}{n_{inv}} - E_{PV,t} \cdot n_{con,pv}\right) / n_{con,fc}$$

Case B2.1.1: *For* $E_{fc,t} > E_{fc,max}$ → $E_{disch,t} = E_{fc,t} - E_{fc,max}$

Case B2.1.2: *For* $E_{fc,t} \leq E_{fc,max}$

- ***Case B2.1.2.1***, *for* $E_{fc,t} \geq E_{fc,min}$
- ***Case B2.1.2.2***, *for* $E_{fc,t} < E_{fc,min}$ → $E_{charge,t} = E_{fc,min} - E_{fc,t}$

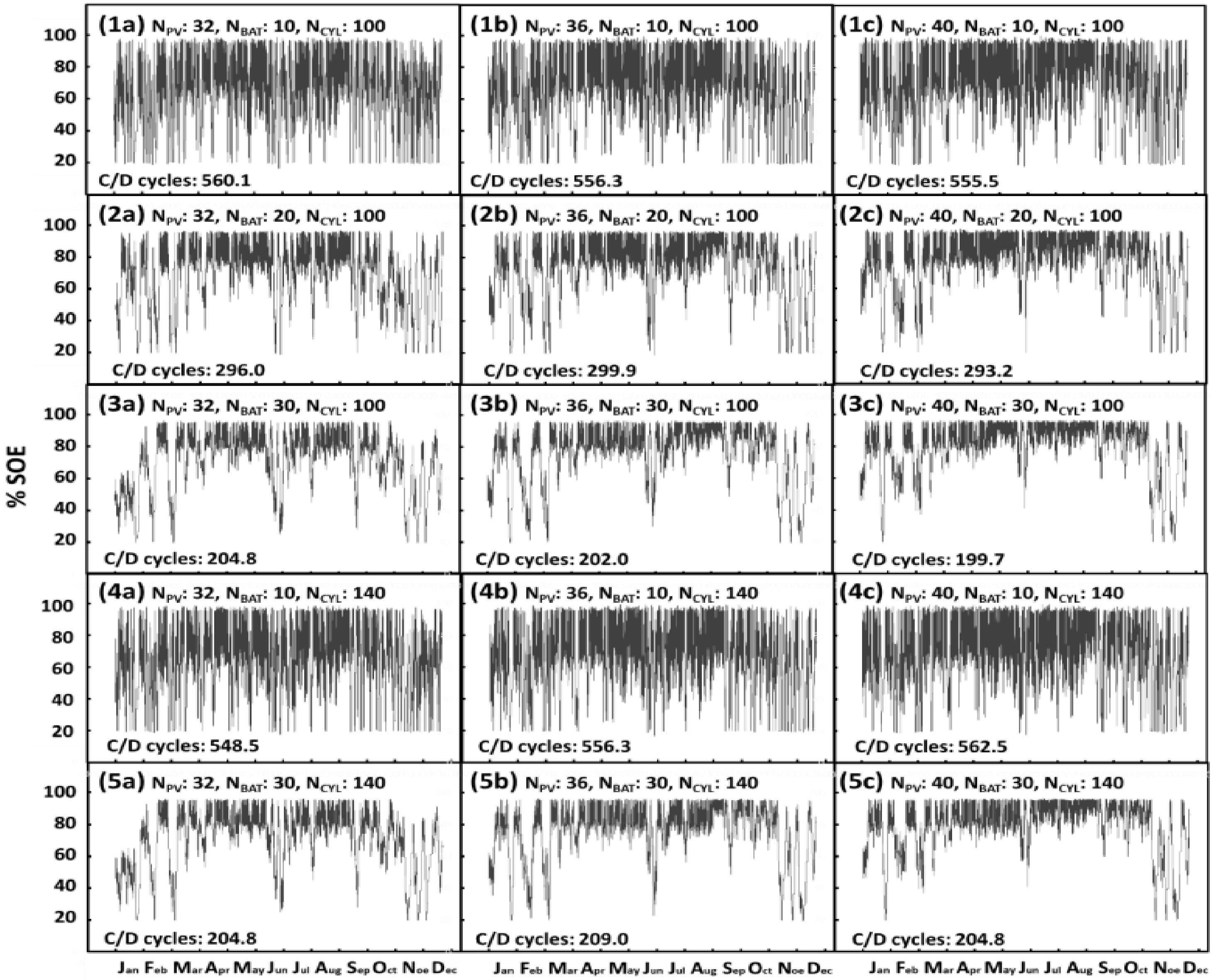
Case B2.2, Operation of the Diesel Generator.



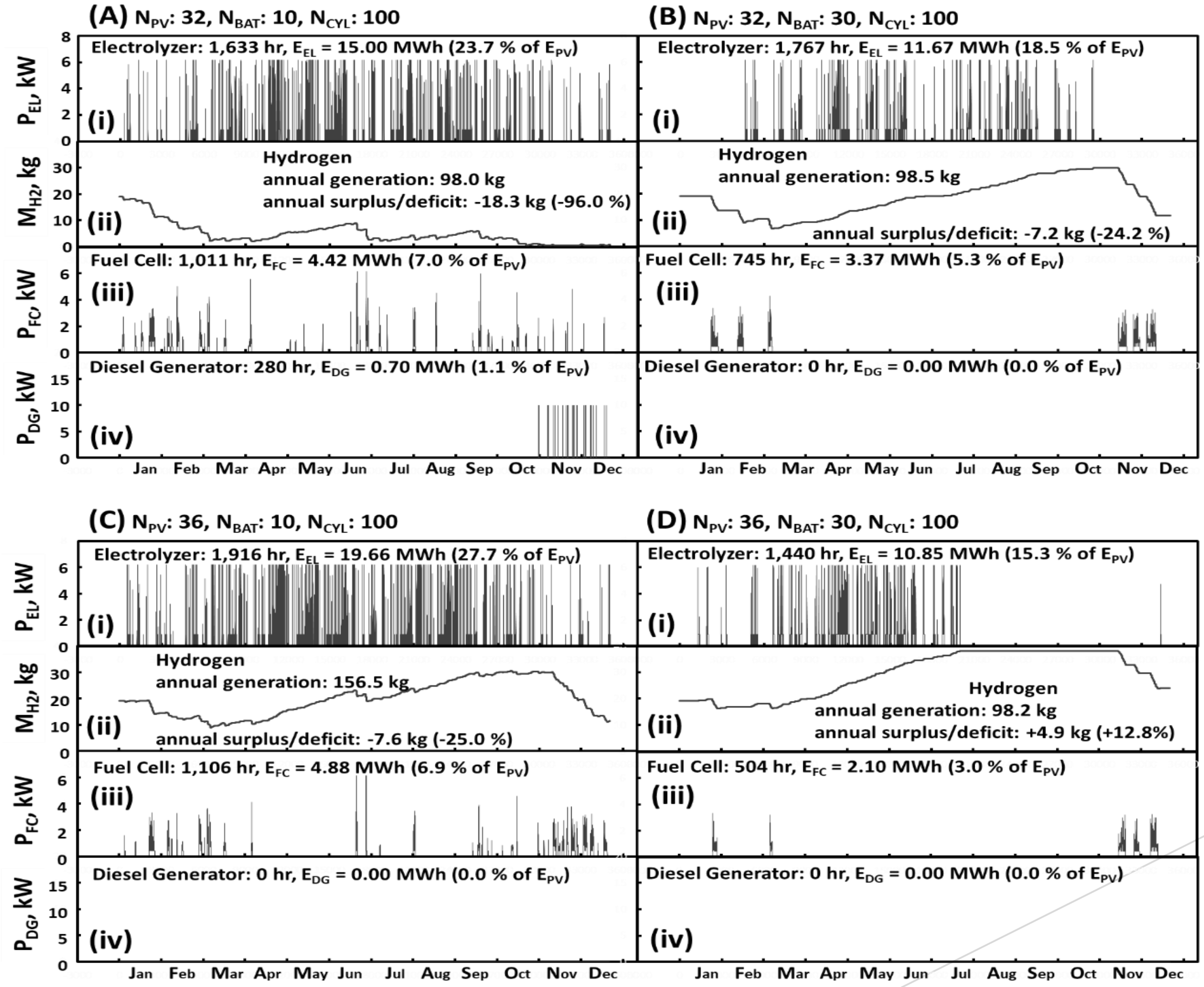
<u>440 examined combinations</u> of nominal PV power, battery's storage capacities and H_2 cylinders volumes (cylinder volumes 4 – 7 m^3 , corresponding to 80 – 140 cylinders).

N_{BAT} – number of battery cells in the battery bank (kWh of the battery bank capacity)	N_{PV} – number of PV-modules in the PV-array (kW of the PV-array nominal power)									
	31 (9.61)	32 (9.92)	33 (10.23)	34 (10.54)	35 (10.85)	36 (11.16)	37 (11.47)	38 (11.78)	39 (12.09)	40 (12.40)
10 (50)	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
12 (60)	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
14 (70)	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
16 (80)	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
18 (90)	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
20 (100)	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
22 (110)	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
24 (120)	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
26 (130)	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
28 (140)	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
30 (150)	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
	15.31 (18.1)	15.80 (22.0)	16.30 (25.8)	16.79 (29.6)	17.28 (33.4)	17.78 (37.2)	18.27 (41.0)	18.76 (44.8)	19.26 (48.6)	19.75 (52.5)
	MWh of Annual PV generation (% PV energy excess with respect to the 12.96 MWh of annual load)									

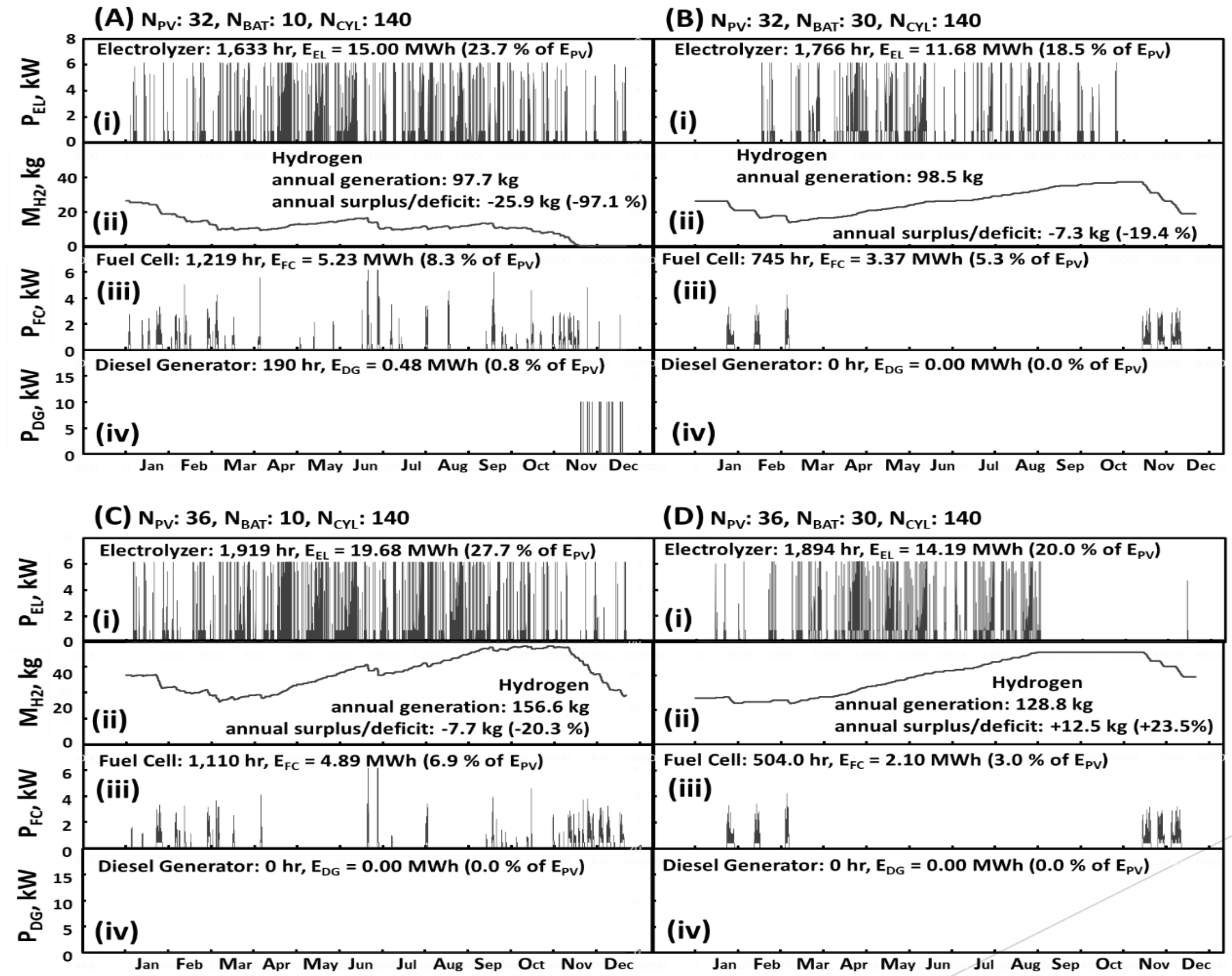
The batteries' bank state of energy (SOE) annual variation, for selected $N_{PV}/N_{BAT}/V_{CYL}$ combinations.



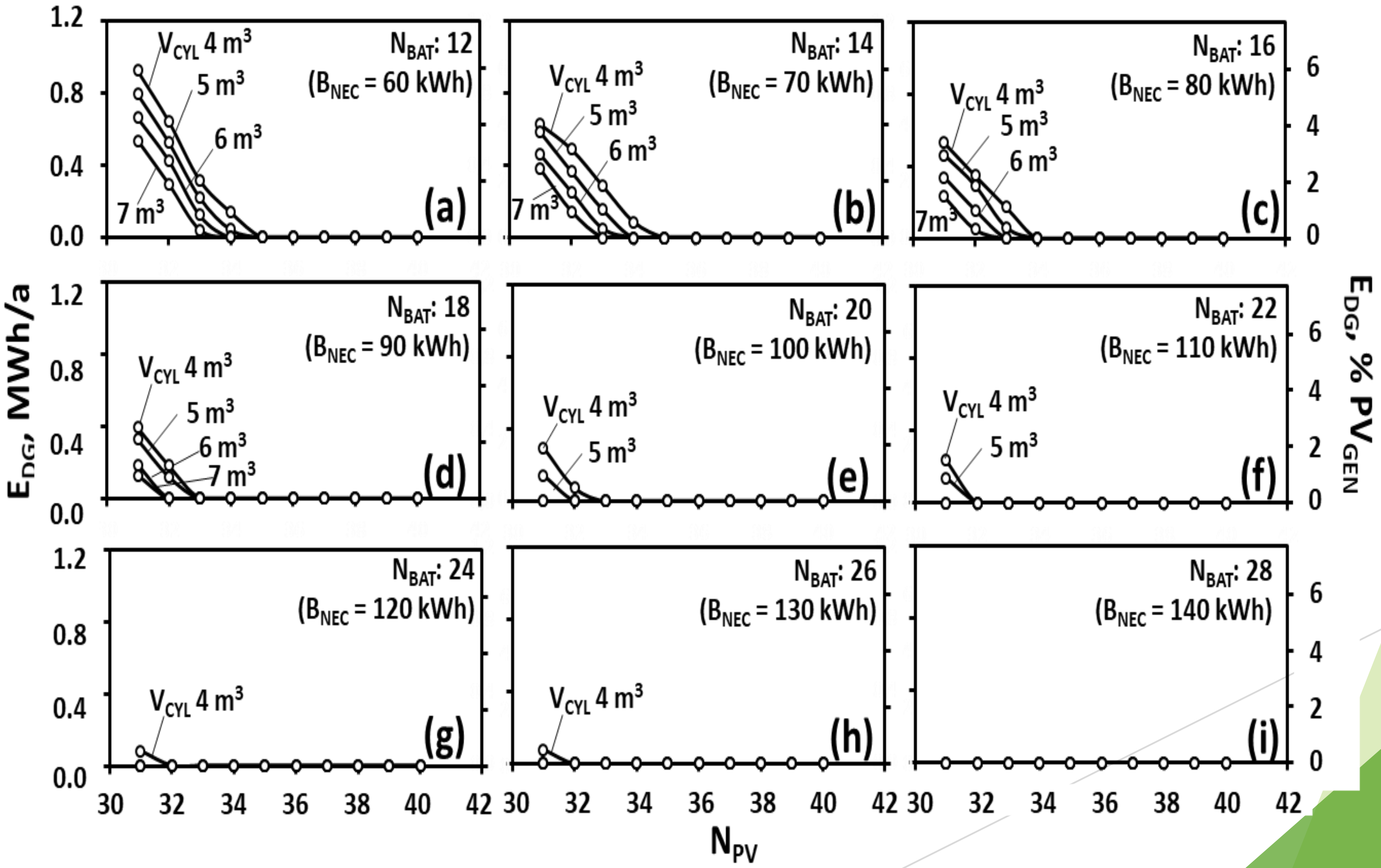
The hydrogen system and the diesel generator annual operation, for 5 m^3 H_2 storage volume.



The hydrogen system and the diesel generator annual operation, for 7 m^3 H_2 storage volume.



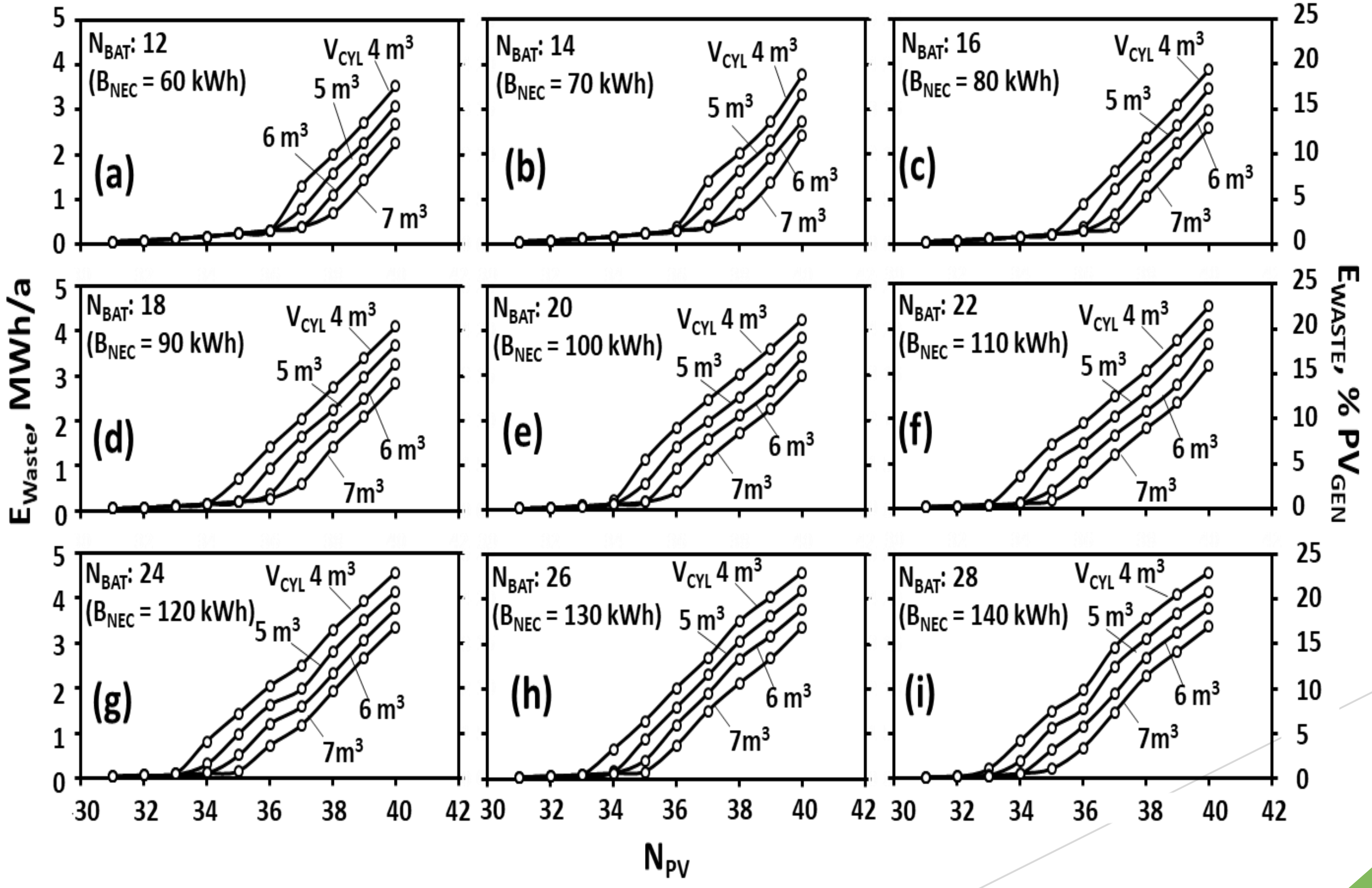
DG generation for B_{NEC}: 60 – 140 kWh, and the total examined number of PV modules and H_2 storage cylinders.



Required H_2 storage volumes (V_{CYL}, m^3) for zero DG generation, for the examined number of installed PV modules (N_{PV}) and batteries elements (N_{BAT}).

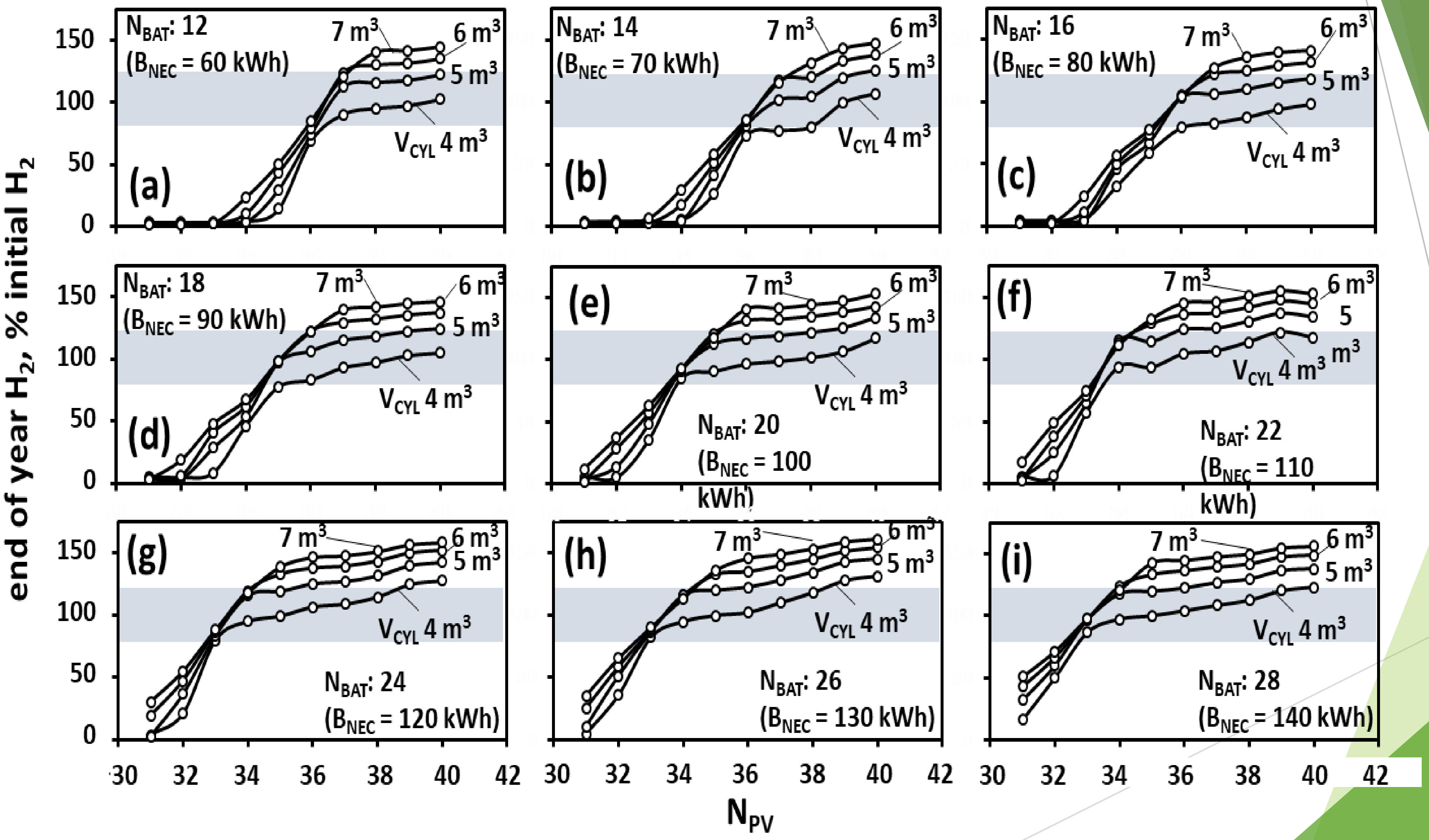
N_{BAT} – number of battery elements in the battery bank (kWh of the battery bank capacity)	N_{PV} – number of PV-modules in the PV-array (kW of the PV-array nominal power output)									
	31 (9.61)	32 (9.92)	33 10.23)	34 (10.54)	35 (10.85)	36 (11.16)	37 (11.47)	38 (11.78)	39 (12.09)	40 (12.40)
10 (50)				7	4-7	4-7	4-7	4-7	4-7	4-7
12 (60)				6-7	4-7	4-7	4-7	4-7	4-7	4-7
14 (70)			7	5-7	4-7	4-7	4-7	4-7	4-7	4-7
16 (80)			5-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
18 (90)		6-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
20 (100)	6-7	5-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
22 (110)	6-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
24 (120)	5-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
26 (130)	5-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
28 (140)	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7
30 (150)	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7	4-7

Wasted PV generation for B_{NEC}: 60 – 140 kWh, and the total examined number of PV modules and H_2 storage cylinders



N_{BAT} – number of battery elements in the battery bank (kWh of the battery bank capacity)	N_{PV} – number of PV-modules in the PV-array (kW of the PV-array nominal power output)									
	31 (9.61)	32 (9.92)	33 10.23)	34 (10.54)	35 (10.85)	36 (11.16)	37 (11.47)	38 (11.78)	39 (12.09)	40 (12.40)
10 (50)	4-7	4-7	4-7	4-7	4-7	4-7	5-7	6-7		
12 (60)	4-7	4-7	4-7	4-7	4-7	4-7	5-7			
14 (70)	4-7	4-7	4-7	4-7	4-7	5-7	6-7			
16 (80)	4-7	4-7	4-7	4-7	4-7	5-7	7			
18 (90)	4-7	4-7	4-7	4-7	5-7	7				
20 (100)	4-7	4-7	4-7	5-7	6-7					
22 (110)	4-7	4-7	4-7	5-7	7					
24 (120)	4-7	4-7	4-7	6-7	7					
26 (130)	4-7	4-7	4-7	6-7	7					
28 (140)	4-7	4-7	5-7	6-7						
30 (150)	4-7	4-7	5-7	7						

Hydrogen excesses or shortages, for BNEC: 60 – 140kWh, and the total examined number of PV modules and H_2 storage cylinders



Required H_2 storage volumes (V_{CYL}, m^3) for the annual H_2 excesses/shortages within ± 20 % of initially stored H_2, for the examined N_{PV} and N_{BAT}.

N_{BAT} – number of battery elements in the battery bank (kWh of the battery bank capacity)	N_{PV} – number of PV-modules in the PV-array (kW of the PV-array nominal power output)									
	31 (9.61)	32 (9.92)	33 10.23)	34 (10.54)	35 (10.85)	36 (11.16)	37 (11.47)	38 (11.78)	39 (12.09)	40 (12.40)
10 (50)							4-7	4-5	4-5	4
12 (60)						7	4-5	4-5	4-5	4
14 (70)						5-7	5-7	4-5	4-5	4
16 (80)						5-7	4-5	4-5	4-5	4-5
18 (90)					5-7	4-5	4-5	4-5	4	4
20 (100)				4-7	4-5	4-5	4-5	4	4	4
22 (110)				4-7	4-5	4	4	4		
24 (120)			4-7	4-7	4-5	4	4	4		
26 (130)			4-7	4-7	4-5	4	4	4		
28 (140)			4-7	4-5	4-5	4	4	4		
30 (150)			4-7	4-5	4	4	4			

Required H_2 storage volumes (V_{CYL}, m^3) for:

(i) zero DG generation,

(ii) zero waste and

(iii) annual H_2 excesses/shortages in the range of ± 20 % of initially stored H_2,

for the examined number of installed PV modules (N_{PV}) and batteries elements (N_{BAT}).

N_{BAT} – number of battery elements in the battery bank (kWh of the battery bank capacity)	N_{PV} – number of PV-modules in the PV-array (kW of the PV-array nominal power output)									
	31 (9.61)	32 (9.92)	33 10.23)	34 (10.54)	35 (10.85)	36 (11.16)	37 (11.47)	38 (11.78)	39 (12.09)	40 (12.40)
10 (50)							5-7			
12 (60)						4-7	6-7			
14 (70)						5-7	6-7			
16 (80)						5-7				
18 (90)					5-7					
20 (100)				5-7						
22 (110)				5-7						
24 (120)			**4-7**	6-7						
26 (130)			4-7	6-7						
28 (140)			5-7							
30 (150)			5-7							
MWh of Annual PV generation (% PV energy excess with respect to the 12.96 MWh of annual load)	15.31 (18.1)	15.80 (22.0)	16.30 (25.8)	16.79 (29.6)	17.28 (33.4)	17.78 (37.2)	18.27 (41.0)	18.76 (44.8)	19.26 (48.6)	19.75 (52.5)