The Norwegian University of Science and Technology
Department of physics

ENGLISH + NORWEGIAN
Norsk oversettelse av oppgavene på s 8-10

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EXAM IN TFY 4300 Energy and environmental physics

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Duration: 9-13

Number of pages: 10

Permitted aids: Calculator

Physical parameters and lists of equations are given in the appendix. A translation of the problems to Norwegian is found on page 8-10 in the appendix.

You can answer in either Norwegian or English, and you have to answer all questions in all 5 problems. The weight for each question is given in the parenthesizes.

Problem 1. (20%) Weather and climate

a) (5%) Lapse rates
You are planning to climb to the top of mountain Gråkallen (552 m above sea level) from "Ravnkloa" at sea-level (0 m) where the temperature is 25°C.
- What temperature should you expect at the top? Consider dry air and that c_p is constant. The dry adiabatic lapse rate is Γ_d=0.01°C/m.
- What would the temperature at the top be if the air was saturated with water vapour? The saturated adiabatic lapse rate is taken to be Γ_s=0.006°C/m.
- Why is $\Gamma_s<\Gamma_d$?

b) (5%) The oceans
- Explain why the oceans are an important part of the climate system.

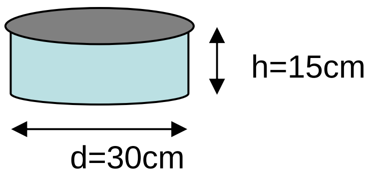
c) (5%) Delay
Assume a constant radiative forcing of ΔI= 5W/m^2, a gain of G_f=0.9 Km^2/W and a time constant of τ_e=30 years.
- What is the final value for ΔT_s caused by the radiative forcing, e.g. what is $(\Delta T_s)_{ss}$?
- Plot how ΔT_s increases with time.
- How many years does it take for ΔT_s to reach half of its final value?

d) (5%) El Niño
- Explain what the "El niño Southern Oscillation" is and how it occurs.
- Where and when does the phenomenon occur and for how long does it last?

Problem 2. (25%) Heat transport and solar water heating

a) (5%) Why is heat transport an important issue in energy physics/technology?

b) (10%) Convective cooling of a cooking pot with lid

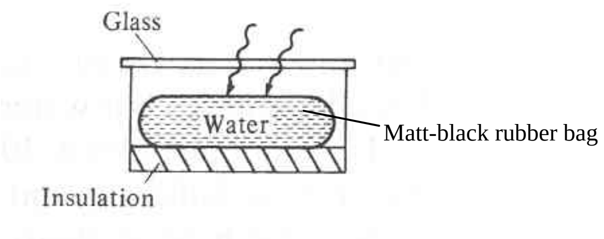


A metal cooking pot with shiny outside surface, of dimensions shown to the right, is filled with food and water and placed on a cooking stove indoors. Assume that the lid is tight and has the same diameter as the pot it self. Neglect heat loss by radiation, and assume that the pot and the lid have a surface temperature of 100°C. The surroundings have a temperature of 16°C.

- What is the minimum energy required to maintain the pot at 100°C for 30 minutes if it is sheltered from the wind?

c) (5%) Solar water heater

- Explain how the solar water heater in the figure on the right works. Give details about the typical properties of the various parts.



- What measures have been taken to optimize the heat gain and minimize the heat loss compared to a solar water heater consisting of an open water container placed directly on the ground?

d) (5%) You are supposed to coat the upper glass sheet and the rubber bag in the drawing in c) with (ideal) coatings that optimize the heat gain and minimize the heat loss for the solar water heater.
  - Should the two coatings/surfaces have the same optical properties? Why/why not?
  - Explain what a selective surface is.
  - Sketch curves for the (ideal) wavelength dependence for the emittance $\varepsilon(\lambda)$ for the coating/selective surface on the glass and on the rubber bag. (Indicate the important wavelength ranges, with typical values.)

Problem 3. (15%) Wind energy

a) (5%) Wind turbine power
  - Give an expression for the power generated by a wind turbine in a wind of speed u_o and air density ρ, intercepting a cross-section A of the wind front.
  - What does the power coefficient C_P tell us?
  - What is the maximal value of C_P? Why is it not 100%? (i.e. Why can we not extract 100% of the energy in the wind?)

b) (5%) The electricity consumption in Norway is ca 110TWh per year. How many windmills with a diameter of 80m are needed to supply 25% of this consumption by wind energy?

Assume that the wind blows at 13m/s 1/3 of the time (and that there is no wind at other times), an air density of 1.2 kgm^{-3}, and that the efficiency of the windmill is 50% of the maximum theoretical value.

c) (5%) If the same amount of electricity (110TWh/year) should be provided by a typical coal fuelled power plant, approximately how much thermal energy should the coal provide (in kWh per year)?

Problem 4. (15%) The hydrogen society

a) (10%) Fuel cells

- Sketch and explain how a fuel cell works. Write down the reaction in the fuel cell.
- What are the advantages by using hydrogen as a fuel?

b) (5%) Hydrogen production and storage

- Give at least two examples on how hydrogen can be produced and two examples of how it can be stored.

Problem 5. (25%) Silicon solar cells

a) (5%) Basic operation

- What is the basic working principle of a typical silicon solar cell?
- Draw energy band diagrams for the cell in the dark and under illumination. Indicate the Fermi level (cell in the dark) and the Fermi level splitting (leading to Quasi Fermi levels) caused by the photogenerated carriers.

b) (10%) Equivalent circuit for an ideal solar cell

- Make a drawing of an equivalent circuit of an ideal solar cell under illumination, with the photogenerated current I_L indicated as a current source.
- Indicate the currents that flow in the circuit when the cell is under illumination, and write down an expression for the current that can be extracted from the solar cell.
- Use this expression find an expression for the short circuit current and for the open circuit voltage. What do these parameters represent?

c) (10%) Equivalent circuit for a real solar cell

- Next make a new equivalent circuit drawing and include series resistance and shunt resistance in the solar cell.
- From the circuit derive expressions for the current and voltage delivered by the solar cell during operation.
- What is the effect of a large series resistance and a low shunt resistance on the efficiency of the solar cell?

APPENDIX

Physical constants

Planck's constant: $h = 6.626\times10^{-34}$ Js

The speed of light: $c = 2.998\times10^{8}$ m/s

Boltzmann's constant: $k = 1.38\times10^{-23}$ J/K

Stefan-Boltzmann's constant: $\sigma = 5.672\times10^{-8}$ W/(m^{2}K^4)

Avogadro's number: $N_A = 6.022\times10^{23}$ mol^{-1}

The electron charge: $e = 1.602\times10^{-19}$ C

The radius of the sun: $r_s = 6.96\times10^{8}$ m

The radius of the earth: $r_e = 6.4\times10^{6}$ m

The sun-earth distance: $\mathrm{d}_{se} = 1.49\times10^{11}$ m

List of equations

$pV = nRT$ $p = \rho R_{air} T$ $\frac{\partial p}{\partial z} = -\frac{p}{H}$ $\frac{\partial T}{\partial z} = -\frac{g}{c_p} = -\Gamma_d$ $E = h\upsilon$ $I_E dE = \frac{2\pi\nu^3}{c^2}\frac{1}{e^{h\upsilon/kt}-1}dE$ $I_\lambda = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kt}-1}$ $\lambda_{\max} T = 2898[\mu m\ K]$ $I(T) = \sigma T^4$ $\Delta T_s = G\Delta I$ $G_f = \frac{G}{1-\sum_n GH_n}$ $\Delta T_s = G_f \Delta I$ $\Delta T_s(t) = (\Delta T_s)_{ss}(1-e^{-t/\tau})$ $P_T = IV$	$P_{ij} = \frac{\Delta T}{R_{ij}}$ $q = \frac{P}{A} = \frac{\Delta T}{r}$ $r = \frac{1}{h} = RA$ $r_n = \frac{\Delta x}{k}$ $\quad R_n = \frac{\Delta x}{kA}$ $r_v = \frac{X}{\mathcal{N} k}$ $\quad R_v = \frac{X}{\mathcal{N} kA}$ $r_r = \frac{(T_1-T_2)}{q}$ $\quad R_r = \frac{(T_1-T_2)}{P_{12}}$ $P_v = A\mathcal{N}\frac{k(T_s-T_f)}{X}$ $\mathcal{R} = \frac{uX}{\nu}$ $\mathcal{A} = \frac{g\beta X^3\Delta T}{\kappa\nu}$ $P_m = \frac{dm}{dt}c(T_3-T_1)$ $P_m = \frac{dm}{dt}\Lambda$ $-mc\frac{d}{dt}(T_1-T_0) = \frac{(T_1-T_0)}{R_{10}}$	$\alpha_\lambda + \rho_\lambda + \tau_\lambda = 1$ $P_r = A\varepsilon\sigma T^4$ $P_{12} = \sigma(T_1^4 - T_2^4)A_1F_{12}$ $P_{12} = A_1F_{12}^{'}\sigma(T_1^2+T_2^2)(T_1+T_2)(T_1-T_2)$ $R_r = \left[A_1F_{12}^{'}\sigma(T_1^2+T_2^2)(T_1+T_2)\right]^{-1}$ $P_{net} = \tau_{\mathrm{cov}}\alpha_p A_p G - \frac{T_p - T_a}{R_L} = \eta_{sp}A_p G$ $P_u = \eta_{pf}P_{net} = \begin{cases} mc\frac{dT_f}{dt} \\ \frac{dm}{dt}c(T_2-T_1) \end{cases}$ $mc\frac{dT_r}{dt} = \tau\alpha GA + P_{boost} - \frac{(T_r-T_a)}{R}$ $\eta = \frac{W}{Q_H} = 1-\frac{Q_C}{Q_H}$ $\eta_{Carnot} = 1-\frac{T_C}{T_H}$ $COP = \frac{Q_C}{W_{in}}$ $B = (U-U_f) + p_o(V-V_f) - T_o(S-S_f)$ $B = Q\left(1-\frac{T_0}{T_H}\right)$

$c = 2c_g = \frac{g}{2\pi}T$	$V_B = V_{bi} = \frac{E_g}{e} - \left(\phi_n + \phi_p\right)$
$E = k_E H^2; \quad k_E = \frac{\rho g}{8}$	$I_p = ep\mu_p\mathscr{E} - eD_p\frac{dp}{dx}$
$J = c_g E$	$I_n = en\mu_n\mathscr{E} + eD_n\frac{dn}{dx}$
$J = k_J T H^2; \quad k_J = \frac{\rho g^2}{32\pi}$	$I_D = I_p + I_n$
$E = \rho g H^2/8$	$I_D = I_r - I_g;\ I_g = I_0 \ \wedge \ I_r = I_0 \exp\left(\frac{eV}{kT}\right)$
$E = \rho g \int_0^\infty S(f)\,\mathrm{d}f \equiv \rho g H_s^2/16$	$I(V) = I_L - I_D = I_L - I_0\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$
	$\Delta\mu = E_{Fn} - E_{Fp} = eV$
$^{235}\mathrm{U} + \mathrm{n} \rightarrow {}^{236}\mathrm{U} \rightarrow X + Y + \upsilon\mathrm{n} + \text{energy}$	$\eta = \frac{I_m \cdot V_m}{P_{in}} = FF \cdot \frac{I_{sc} \cdot V_{oc}}{P_{in}}$
$\eta = \nu\frac{N(235)\sigma_f(235)}{N(235)\left[\sigma_f(235) + \sigma_c(235)\right] + N(238)\sigma_c(238)}$	$FF = \frac{I_m \cdot V_m}{I_{sc} \cdot V_{oc}}$
$\frac{dN}{dt} = \frac{\rho N}{l}$	$\rho = \frac{(n_0 - n_1)^2}{(n_0 + n_1)^2}$
$l^* = (1-\beta)l + \beta t_d$	
$^2\mathrm{D} + {}^3\mathrm{T} \longrightarrow {}^4\mathrm{He} + {}^1\mathrm{n} + 17.6\mathrm{MeV}$	
$P_L = \alpha n^2\sqrt{kT} + 3n\frac{kT}{\tau_E}$	$P_T = C_P A\frac{\rho u_0^3}{2}$
$P_{th} = \langle\sigma u\rangle E\frac{n^2}{4}$	$P_o = A\frac{\rho u_0^3}{2}$
$P_T = P_L + P_{th}$	$F_A = \frac{\Delta\mathrm{p}}{\Delta t} = \frac{m(u_0 - u_2)}{\Delta t} = \rho A_1 u_1(u_0 - u_2)$
$\eta P_T > P_L$	$F_A = A_1(p_{1u} - p_{1d}) = A_1\rho(u_0^2 - u_2^2)/2$
	$P = u_1 F_A$
$CO_2 + H_2\dot{O} \xrightarrow{light} \dot{O}_2 + \left[CH_2O\right] + H_2O$	$P_T = u_1 F_A = u_1\frac{dm}{dt}(u_0 - u_2)$
	$P_T = \frac{1}{2}\frac{dm}{dt}(u_0^2 - u_2^2)$
	$a = \frac{u_0 - u_1}{u_0}$
	$P_T = \left[4a(1-a)^2\right]P_0$
	$C_P \le \frac{16}{27}$

Table B.1 Physical Properties of dry air at atmospheric pressure. ($\mathcal{A}$ is the Raleigh number, X the characteristic dimension)

Temperature T	*Density* ρ	*Specific heat* $c_{(p)}$	*Kinematic viscosity* $\nu = \mu/\rho$	*Thermal diffusivity* κ	*Thermal conductivity* k	*Prandtl number* $\mathcal{P}$	$\mathcal{A}/X^3\Delta T$
°C	$kg\,m^{-3}$	$10^3\,J\,kg^{-1}\,K^{-1}$	$10^{-6}\,m^2\,s^{-1}$	$10^{-6}\,m^2\,s^{-1}$	$10^{-2}\,W\,m^{-1}\,K^{-1}$		$10^8\,m^{-3}\,K^{-1}$
0	1.30	1.01	13.3	18.4	2.41	0.72	1.46
20	1.20	1.01	15.1	20.8	2.57		1.04
40	1.13	1.01	16.9	23.8	2.72		0.78
60	1.06	1.01	18.8	26.9	2.88	0.70	0.58
80	1.00	1.01	20.8	29.9	3.02		0.45
100	0.94	1.01	23.0	32.8	3.18	0.69	0.34
200	0.75	1.02	34.6	50	3.85	0.68	0.12
300	0.62	1.05	48.1	69	4.50		0.052
500	0.45	1.09	78	115	5.64		0.014
1000	0.28	1.18	174	271	7.6	0.64	0.0016

Other properties of air:

Velocity of sound in air (at 15°C) = $340\,m\,s^{-1}$
Coefficient of diffusion of water vapor in air (at 15°C) = $25 \times 10^{-6}\,m^2\,s^{-1}$
Coefficient of self-diffusion of N_2 or O_2 in air (at 15°C) = $18 \times 10^{-6}\,m^2\,s^{-1}$
Coefficient of thermal expansion (at 27°C) $\beta = (1/T) = 0.0033\,K^{-1}$

Table C.2 Free convection. Comparative tables in other texts may refer to Grashof number $\mathcal{G} = \mathcal{A}/\mathcal{P}$

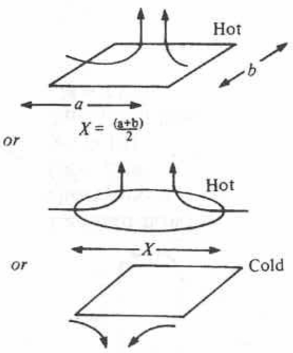
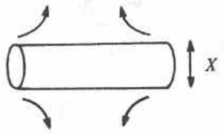
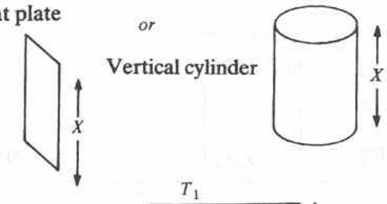
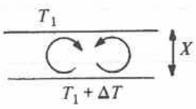
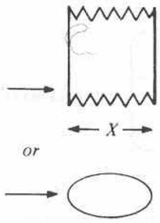
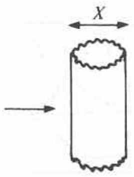
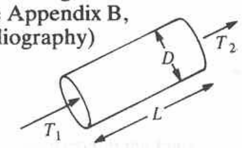
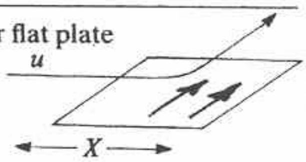
Shape		Case	Overall Nusselt number	Equation no.
Horizontal flat plate		Laminar ($10^2 < \mathcal{A} < 10^5$)	$\mathcal{N} = 0.54\mathcal{A}^{0.25}$	(C.1)
		Turbulent ($\mathcal{A} > 10^5$)	$\mathcal{N} = 0.14\mathcal{A}^{0.33}$	(C.2)
Horizontal cylinder		laminar ($10^4 < \mathcal{A} < 10^9$)	$\mathcal{N} = 0.47\mathcal{A}^{0.25}$	(C.3)
		turbulent ($\mathcal{A} > 10^9$)	$N = 0.10\mathcal{A}^{0.33}$	(C.4)
Vertical flat plate		If laminar, ($10^4 < \mathcal{A} < 10^9$)	$\mathcal{N} = 0.56\mathcal{A}^{0.25}$	(C.5)
		If turbulent, ($10^9 < \mathcal{A} < 10^{12}$)	$\mathcal{N} = 0.20\mathcal{A}^{0.40}$	(C.6)
Parallel plates (slope <50°)		Turbulent ($\mathcal{A} > 10^5$)	$\mathcal{N} = 0.062\mathcal{A}^{0.33}$	(C.7)

Table C.3 Forced convection

Shape		Case	Overall Nusselt number	Equation no.
Flow over flat plate		Laminar ($\mathcal{R} < 5 \times 10^5$)	$\mathcal{N} = 0.664\,\mathcal{R}^{0.5}\mathcal{P}^{0.33}$	(C.8)
		Turbulent ($\mathcal{R} > 5 \times 10^5$)	$\mathcal{N} = 0.37\,\mathcal{R}^{0.8}\mathcal{P}^{0.33}$	(C.9)
Flow over circular cylinder		Laminar ($0.1 < \mathcal{R} < 1000$)	$\mathcal{N} = (0.35 + 0.56\,\mathcal{R}^{0.52})\mathcal{P}^{0.3}$	(C.10)
		Turbulent ($10^3 < \mathcal{R} < 5 \times 10^4$)	$\mathcal{N} = 0.26\,\mathcal{R}^{0.6}\mathcal{P}^{0.3}$	(C.11)
Flow *inside* a circular pipe: from Wong, 1977 (see Appendix B, Bibliography) 	Laminar flow, short pipe ($\mathcal{R} < 2300$, $\mathcal{G}_1 > 10$)		Graetz number $\mathcal{G}_1 = \mathcal{R}\mathcal{P}(D/L)$ $= 4Q/\kappa\pi L$	(C.12)
			$\mathcal{N} = 1.86\,\mathcal{G}_1^{\,0.33}$	(C.13)
	Turbulent flow ($\mathcal{R} > 2300$)		$\mathcal{N} = 0.027\,\mathcal{R}^{0.8}\,P^{0.33}$	(C.14)
	General		$P = \rho c Q(T_2 - T_1)$	(2.6)

〰 Indicates section of an extended shape

Table C.4 Mixed convection (forced and free together)

Shape	Case	Formula	
Air over flat plate 	$X > 0.1\,\text{m}$ $u < 20\,\text{m}\,\text{s}^{-1}$	$h = a + bu$ $[a = 5.7\,\text{Wm}^{-2}\,\text{K}^{-1}$ $b = 3.8\,(\text{Wm}^{-2}\,\text{K}^{-1})/(\text{ms}^{-1})]$	(C.15)
General		$\mathcal{N}_1 = \max(\mathcal{N}_{\text{forced}}, \mathcal{N}_{\text{free}})$	
		$\mathcal{N}_1 < \mathcal{N}_{\text{mixed}} < \mathcal{N}_{\text{forced}} + \mathcal{N}_{\text{free}}$	(C.16)

NORSK OVERSETTELSE:
Du kan svare enten på norsk eller engelsk, og du må svare på alle spørsmålene i alle 5 oppgavene. Vekten er hver oppgave er gitt i parentes foran hver deloppgave.

Oppgave 1. (20%) Vær og klima

a) (5%) Vertikal temperaturgradient
Du har tenkt å bestige Gråkallen (552 moh) fra Ravnkloaved havnivå (0 moh) hvor temperaturen er 25°C.
- Hvilken temperatur kan du vente deg på toppen? Anta at lufta er tørr, og at cp er konstant. Vertikal temperaturgradient for tørr luft er Γ_d=0.01°C/m.
- Hva vil temperaturen på toppen være his lufta er mettet med vanndamp? Vertikal temperaturgradient for mettet luft settes lik Γ_s=0.006°C/m.
- Hvorfor er $\Gamma_s<\Gamma_d$?

b) (5%) Havene
- Forklar hvorfor havene er en viktig del av klimasystemet.

c) (5%) Tidsforsinkelse
Anta et konstant strålingspåtrykk på ΔI= 5W/m^2, en forsterkning på G_f=0.9 Km^2/W og en tidskonstant på τ_e=30 år.
- Hva er sluttverdien for temperaturendringen $\Delta T_{s,}$ som skyldes strålingspåtrykket, dvs. hva er $(\Delta T_s)_{ss}$?
- Plott hvordan ΔT_s øker som funksjon av tid.
- Hvor mange år tar det før ΔT_s har nådd halvparten av sluttverdien?

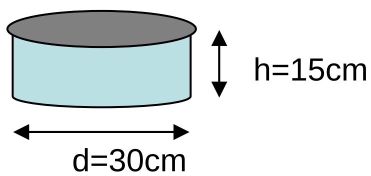
d) (5%) El Niño
- Forklar hva“El niño Southern Oscillation” er og hvordan den oppstår.
- Hvor og når oppstår fenomenet og hvor lenge varer det?

Oppgave 2. (25%) Varmetransport og vannvarming

a) (5%) Hvorfor er varmetransport et viktig tema i energifysikk/-teknologi?

b) (10%) Konveksjonskjøling av en kasserolle med lokk

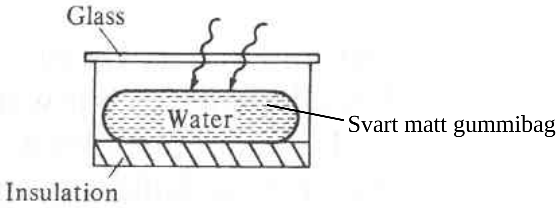
En kasserolle av metall med blank overflate, med dimensjoner vist i figuren til høyre, er fylt med mat og vann og plassert på en komfyr innendørs. Anta at lokket er tett og har samme diameter som kasserollen. Se bort fra varmetap på grunn av varmestråling, og anta at kasserollen og lokket har overflatetemperatur 100°C. Omgivelsene har temperatur 16°C.



- Hvor mye energi trengs det (minst) for å opprettholde kasserollens ytterside på 100°C i 30 minutter.

c) (5%) Soldrevet vannvarmer

- Forklar hvordan sol-vannvarmeren i figuren til høyre fungerer. Ta med detaljer om typiske egenskaper til de ulike delene.



- Hvilke tiltak er gjort for å optimalisere oppvarmingen og redusere varmetapet, i forhold til en sol-vannvarmer som består av et åpen vannbeholder som står rett på bakken?

d) (5%) Du skal belegge den øvre glass overflaten og gummi-bagen i tegningen i c) med (ideelle) belegg som skal optimalisere oppvarmingen og redusere varmetapet for sol-vannvarmerern ytterligere.

- Bør de to beleggene ha de samme optiske egenskapene? Hvorfor/hvorfor ikke?
- Forklar hva en selektiv overflate er.
- Skisser kurver for (den ideelle) bølgelengde-variasjonen for emittansen $\varepsilon(\lambda)$ for belegget/den selektive overflata på glasset og på gummi-bagen. (Indiker de viktige bølgelengdeområdene, med typiske verdier.)

Oppgave 3. (15%) Vindkraft

a) (5%) Effekt produsert i en vindturbin

- Oppgi et uttrykk for effekt generert av en vindturbin i en vindhastighet på u_o og lufttetthet ρ, som fanger inn et tverrsnitt A av vindfronten.
- Hva angir effekt koeffisienten C_P?
- Hva er maksimalverdien til C_P? Hvorfor er den ikke 100%? (dvs hvorfor kan vi ikke utnytte 100% av energien i vinden?)

b) (5%) Elektrisitetsforbruket i Norge er på ca 110TWh per år. Hvor mange vindturbiner med diameter 80m trengs det om vi skal dekke 25% av dette forbruket med vindkraft?

Anta at vinden blåser med 13m/s 1/3 av tiden (og at det er vindstille ellers), en lufttetthet på 1,2 kgm^{-3}, og at vindturbinen har en effektivitet som er 50% av maksimal teoretisk verdi.

c) (5%) Hvis samme mengde elektrisitet (110TWh/år) skulle genereres med et konvensjonelt kullfyrt kraftverk, hvor mye termisk energi må kullet bidra med (målt i kWh per år)?

Oppgave 4. (15%) Hydrogensamfunnet

a) (10%) Brenselcelle

- Skisser og forklar virkemåten til en brenselcelle.
- Hva er fordelene med å bruke hydrogen som brensel?

b) (5%) Hydrogenproduksjon og –lagring

- Gi minst to eksempler på hvordan hydrogen kan produseres og minst to eksempler på hvordan hydrogen kan lagres.

Oppgave 5. (25%) Silisium solceller

a) <u>(5%) Virkemåte</u>

- Hva er den grunnleggende virkemåten til en typisk silisium solcelle?
- Tegn energi diagram for solcella i mørke og under belysning. Indiker Ferminivået (for solcella i mørke) og Fermi-nivåsplittinga (som gir kvasi-Ferminivåene) som skyldes de fotogenererte ladningsbærerne.

b) <u>(10%) Ekvivalentkrets for ideell solcelle</u>

- Tegn en ekvivalentkrets for ei ideell solcelle under belysning, med den fotogenererte strømmen I_L indikert som en strømkilde.
- Indiker strømmene som går i kretsen når solcella belyses, og skriv ned et uttrykk for strømmen som kan leveres av solcella.
- Bruk dette uttrykket til å utlede uttrykk for kortslutningsstrømmen og åpen-krets-spenningen. Hva representerer disse to størrelsene?

c) <u>(10%) Ekvivalentkrets for reell solcelle</u>

- Tegn nå en ekvivalentkrets med seriemotstand og parallellmotstand inkludert i solcella.
- Utled fra ekvivalentkretsen uttrykk for strøm og spenning levert fra solcella i operasjon.
- Hvordan påvirker en stor seriemotstand og en liten parallellmotstand effektiviteten til solcella?